Shelterbelt Influence on Great Plains Field Environment and Crops

A Guide for Determining Design and Orientation

Growth Through Agricultural Progress

Production Research Report No. 62
October 1962
U.S. Department of Agriculture
Forest Service

Acknowledgment

Grateful acknowledgment is made to the many Station staff members who helped make this report possible. The late Carlos G. Bates supervised the studies. Warren E. Barnes carried out much of the fieldwork. Others who participated in the fieldwork were Ronald J. Woolery, W. T. Bagley, John M. Molberg, E. J. Dortignac, Donald U. Usher, J. W. Macon, F. T. Frederickson, and John Hubbard. Donald Manning aided in the collection of data on snow samples and soil moisture studies.

The author also expresses his appreciation for the helpful cooperation of the State agricultural experiment stations and their substations in North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas who made facilities available for threshing grain samples and ginning and grading cotton.

Contents

Shelterbelt Influence on Great Plains Field Environment and Crops

By J. H. Stoeckeler, *Senior Soil Scientist*, Lake States Forest Experiment Station, Forest Service (The Station is maintained by the U.S. Department of Agriculture in cooperation with the University of Minnesota)

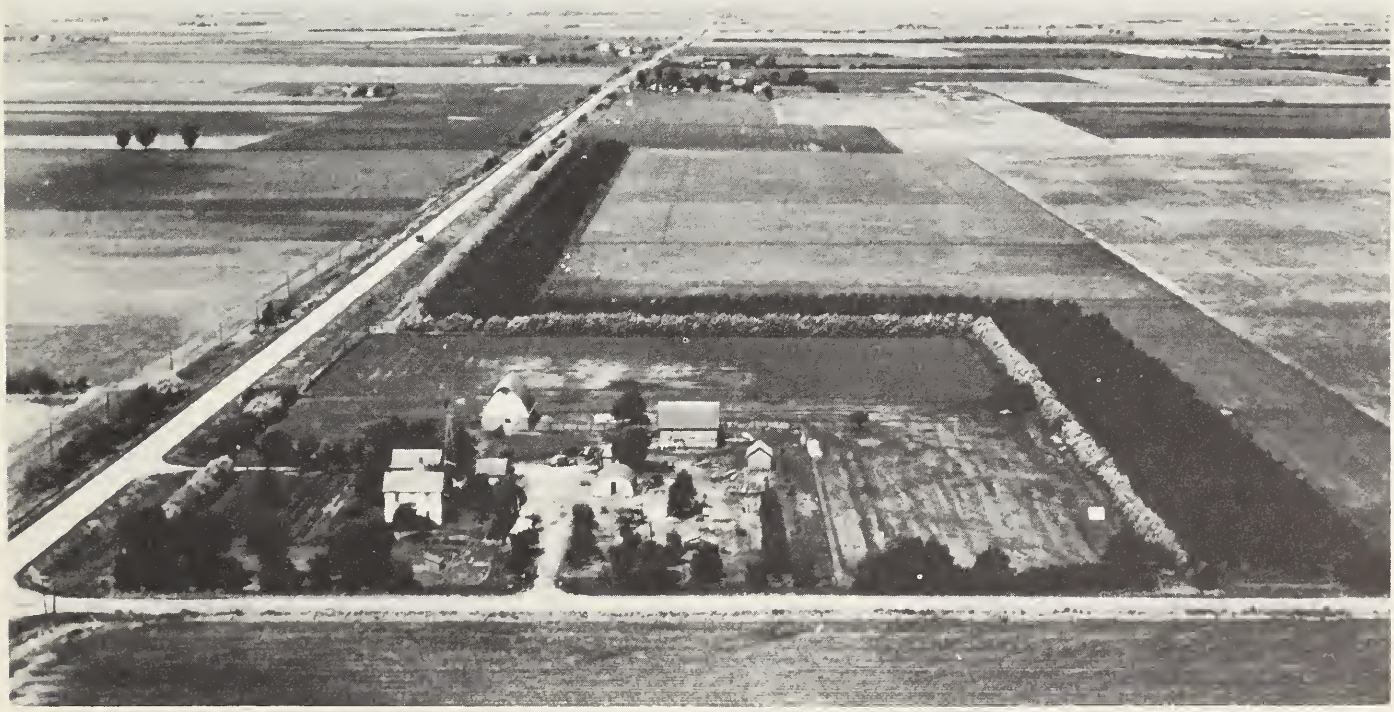
Introduction

Shelterbelts, often called windbreaks, are barriers of trees and shrubs planted to reduce wind velocity, evaporation, and wind erosion; protect crops; control snowdrifting; furnish cover and food for wildlife; or protect homes, farm buildings, and livestock. They are planted across and on the margins of agricultural fields or near farm buildings (fig. 1).

The value of farmstead, livestock, and wildlife shelterbelts has been widely accepted. Although plantings on agricultural fields have been recognized to have definite value in wind-erosion control, their role in the yield of agricultural crops in the Great Plains has not been understood as well. The chief reason for this has been the scarcity of crop-yield data for the sheltered zone of such belts. Since Carlos G. Bates' pioneer effort in 1911 (Bates 1911),[1] very little has been published in this field of research that is applicable in the Great Plains.

This report, therefore, brings together the results of studies of the effects of Great Plains shelterbelts on field environment and crop yields of small grain, corn, and cotton during the period 1935–41. The primary reasons for crop response are discussed, and recommendations are given for the most effective design, orientation, and placement of shelterbelts in relation to adjoining fields.

[1] Author names accompanied by dates of publication refer to the list of Literature Cited, page 24.



SCS NEBR. 1535

Figure 1.—A farmstead in Nebraska protected by a shelterbelt. Its extension at left center serves to protect the nearby agricultural field.

Influence of Shelterbelts on Field Environment

Shelterbelts reduce wind velocity, wind erosion, and mechanical damage to plants. They also alter factors of the microclimate, such as humidity and temperature, in the protected zone. Hence moisture is conserved by reducing evaporation and transpiration, and extra moisture may be trapped in snowdrifts. As a result of such changes in field environment, the favorable effect of shelterbelts on the growth and development of crop plants is registered at harvest.

Reduction of Wind Velocity

Wind, especially when humidity is low, affects crops adversely by placing them under high transpiration stress. It may also cause firing of corn, blowing out of newly seeded grainfields, sandblasting, lodging of grain, or rubbing and consequent degrading of fruit. And on windy days bees do not work actively; they are, of course, an important agent in the pollination of fruits and certain legumes (Rhee 1957, Stoeckeler and Williams 1949).

[2] H refers to one unit of tree or barrier height.

The effect of a barrier on reducing the velocity of strong winds is illustrated by measurements made to the leeward and windward sides of a 16-foot-high fence of 1- by 6-inch boards that had a 6-inch vertical gap between them, or 50 percent density. Wind velocity was reduced 20 percent or more to a distance of about 20 barrier heights to leeward and 50 percent or more to a distance of 10 barrier heights (fig. 2). To the windward side, the reduction was 10 percent or more to a distance of about 5 H.[2] Another effect of the barrier was an upward deflection of air currents as they passed over it.

Low-density shelterbelts reduce wind velocity in a manner fairly similar to that of wood fences of 33-percent density, and their effects on wind velocity are similar (fig. 3). The zone of maximum wind reduction extends to 7 or 8 H, and the maximum percentage reduction may be in the general range of 35 to 45 percent. Dense windbreaks (roughly equivalent to triple fences each of 33-percent density) may reduce wind velocity as much as 70 to 75 percent within 3 H leeward.

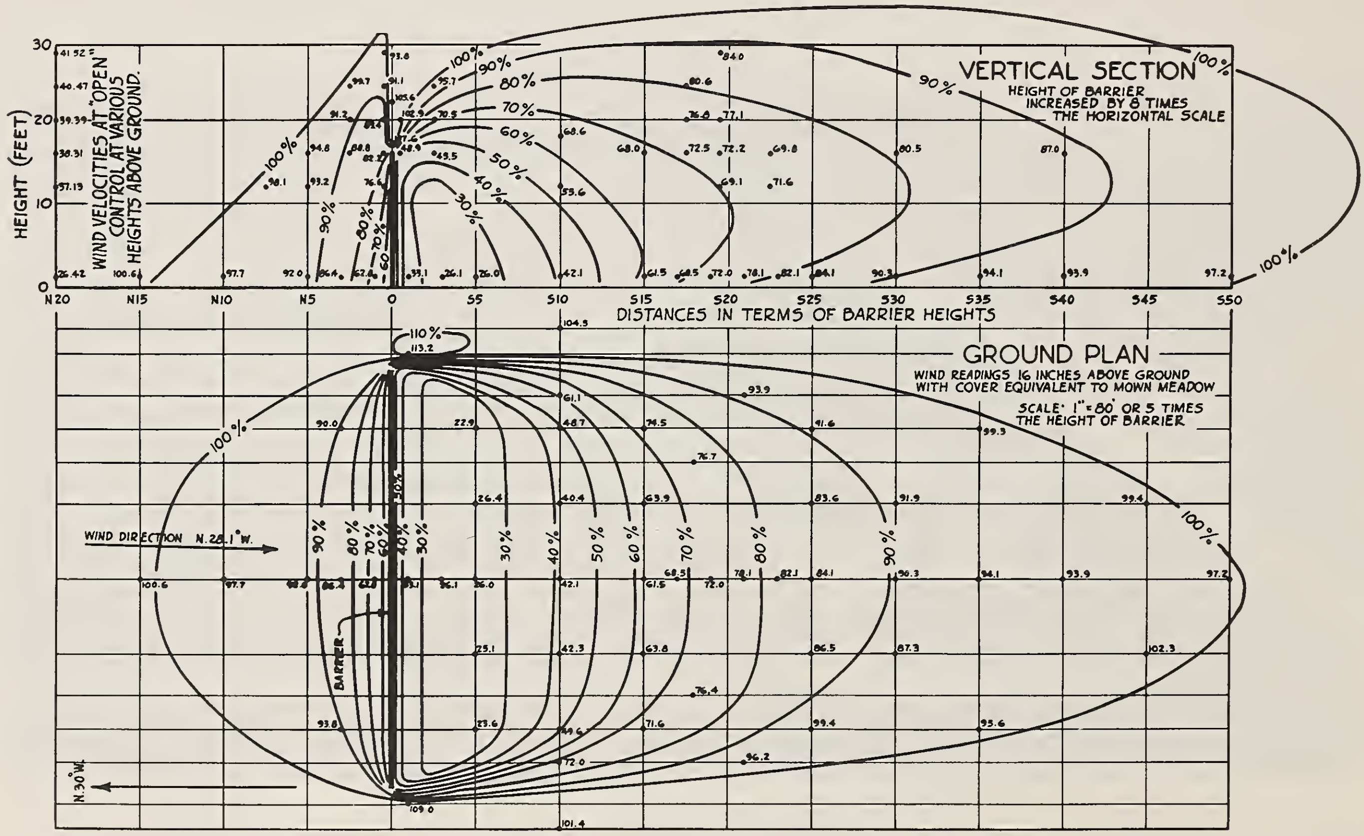


FIGURE 2.—Wind velocity pattern above a mown field during a 38-mile-per-hour wind blowing at a right angle to a 16-foot-high wood fence 400 feet long and of 50-percent density, Huron, S. Dak. Vertical lines represent intervals of 5 barrier heights, with zero indicating the barrier position. Measurements were taken 16 inches above the ground. Percentages are measured in terms of wind velocity in the open.

The chief differences between the 290-foot-wide ash grove and the 125-foot-wide cottonwood and locust grove (fig. 3) were width of belt and density of understory; the cottonwood and locust grove had a uniformly dense understory and a side flanking of black locust which gave it an overall density rating of 75 percent. The wide ash planting was somewhat more open beneath and had an overall density rating of 66 percent. The thin 170-foot-wide cottonwood belt, very open underneath, was rated at 50-percent density; it apparently gave slightly more protection in the zone of 7 to 20 H than did the wide ash belt. The artificial barrier in the lower graph was a triple fence of boards, each fence of 33-percent density, with the center 16-foot-high fence flanked by fences half its height.

Dense and wide shelterbelts are especially desirable for winter protection of farmsteads and feedlots. Those that are narrower and more permeable usually will serve agricultural fields better in northerly areas where there is considerable snowfall. They occupy less space and permit more of the snow to settle on the fields (Bates and Stoeckeler 1942, Stoeckeler and Dortignac 1941).

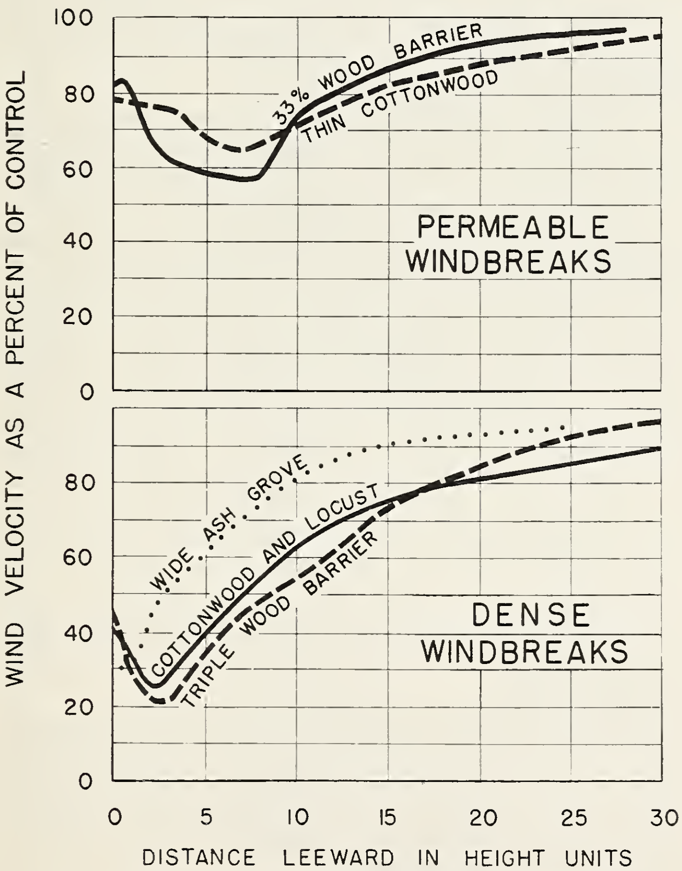


FIGURE 3.—Comparative wind velocity at 16 inches above ground to leeward of several types of planted and wood fence barriers. Wind reductions are on centerline at right angles to the barriers. Zero is the lee face of the barrier. The curve for the ash grove illustrates loss in effectiveness when a stand of trees is open, allowing the wind to sweep under the crowns.

This point is of special importance in the northern Great Plains where snowfall may contribute a substantial amount of soil moisture to cropland. In the central and southern plains where less snow falls, denser shelterbelts may be more desirable.

Substantial wind reductions, with percentages similar to those shown in figure 2, have been observed for very narrow belts, some with as few as one to three rows, particularly when conifers or dense-growing broadleaf trees and shrubs were used (Caborn 1956, Den Uyl 1936, Jensen 1954, Staple and Lehane 1955). Caborn (1957) demonstrated in wind tunnel tests that a narrow belt may be more effective than a wide one in width of the zone of influence.

Reduction of Evaporation

Measurements of the reduction in evaporation along a line across a wood barrier of 50-percent density are given in the following tabulation. Reductions noted in wind velocities, which under open conditions were in the 10- to 15-mile-per-hour range, are also given:

	Reduction in relation to open-field controls [2]	
Direction from barrier and distance [1]	*Evaporation (percent)*	*Wind velocity (percent)*
Windward (south):		
10	0	5
5	7	12
1	20	43
Leeward (north):		
1	23	26
2	21	48
3	35	66
4	33	63
5	31	60
7.5	28	51
10	26	42
15	12	22
20	8	12
25	6	9

[1] Distance is measured in barrier height units (H).

[2] Instruments used were a modification of the Type-6 Forest Service evaporimeters devised by Bates (1919). They had evaporating elements of 100-square-centimeter surface area and were placed on either side of a 12-foot-high east-west wood barrier of 50-percent density. Wind velocity was 10 to 15 m.p.h. in the open. Records were taken on an August day at a height of 6 inches above ground.

The reduction in evaporation was greatest at three barrier heights on the leeward side (north in this instance), coinciding with the point of greatest reduction in wind velocity.

Similar or greater reductions in summer evaporation near shelterbelts, generally from small open vessels, have been reported by other investigators (Bates 1911, Maran and Lhota 1952, Satoo 1952). Staple and Lehane (1955), working with larger free-water evaporation tanks near three-row, 18-foot-high broadleaf shelterbelts in the Canadian Prairie Provinces, showed about a 13-percent reduction in May-to-September evaporation in tanks located within 5 rods of the leeward side of the planting. As might be expected, the

reduction of evaporation was very substantial in summer and fall, moderate in spring, and least in winter.

Matiakin (1937) found evaporation from open vessels to be about 40 percent less in the zone of optimum protection between closely spaced shelterbelts. At the midpoint between plantings, the reduction was 20 percent.

Evaporation from the soil is substantially less than from evaporimeters. Under a situation simulating dryland conditions, Bates (1948a) showed evaporation from bare soil to be only 2.0 to 2.5 percent less on the protected (north) side of a 12-foot-high east-west barrier at about 2 H than under unprotected conditions; there was some effect to about 7.5 H. On the warm (south) side of the barrier, water loss was actually higher to at least 5 H (due to a temperature buildup in midday) than in open unprotected areas; at 1 H on the south side the additional loss was about 3 percent.

Bates' study was done with large metal pots sunk flush with the ground, filled with premixed soil, and kept free of vegetation to simulate summer fallow. The pots were reweighed periodically with a minimum of water added. Bates' conclusions regarding evaporation of soil moisture as affected by shelterbelts are more conservative than those reported in a Russian investigation by Kucheryavykh (1940), who claimed 19- to 26-percent reduction of soil moisture loss from the top 20 centimeters of soil by shelterbelt protection. However, this might be explained by the fact that the soil depths used by Bates were about four times as great as those used by the Russian investigator.

Shelterbelts have been reported to reduce water loss by evaporation during sprinkler irrigation (Gorshenin et al. 1934). They were also reported to reduce evaporation from reservoirs and ponds; these reductions were 15 to 26 percent, depending on the size of the impoundment. The data did not take into consideration water drawn laterally by the trees from the reservoirs and ponds to replace that used in transpiration.

Conservation of Soil Moisture by Trapping of Snow and Reduction of Runoff

Shelterbelts trap drifting snow that might otherwise blow into ditches, roadways, and depressions. In the Great Plains this is of especial importance from Nebraska northward. Shelterbelts, particularly where planted on the contour, also reduce runoff (Beskök 1957).

Some investigators claim that snow blowoff from cropland in prairie areas not protected by shelterbelts may be as much as 50 to 75 percent (Gorshenin et al. 1934), and, as a consequence, protected fields get 2½ to 3 times as much moisture from snow as unprotected land. Panfilov (1937) reports 68-percent blowoff from open land and only 6 percent from fields protected on four sides.

Plantings reduce spring runoff (Chernikov 1951, Suss 1944) partly through the retarding action of snowdrifts on waterflow and partly through the presence of unfrozen or porously frozen soil in or near the tree belt (Dautov 1953, Gordienko 1953, Stoeckeler and Dortignac 1941, Suss 1944) under the deepest part of the snowpack.

Numerous investigators have recorded observations on the large amount of snow trapped by shelterbelts and the recharge of soil moisture due to the snowpack. Belts with dense shrub rows on the windward side tend to trap snow in great depth close to the trees (fig. 4) and prevent its blowing off the fields. Even single rows accomplish this. For instance, in a Canadian study average snow depth near each belt was in the range of 18 to 23 inches while in the open it was only 3 to 7 inches (Staple and Lehane 1955). Wide plantings often tend to trap three-fourths or more of the snow within the zone occupied by trees, with comparatively little deposited on nearby agricultural fields where it will benefit crop growth. More permeable shelterbelts, which are somewhat open below, tend to deposit the snow as a more uniform but thinner blanket on nearby fields and thus furnish more soil moisture for crop growth (fig. 5).

The effect of shelterbelt width and density on snow distribution must be considered in connection with shelterbelt design in the Northern Plains. Comparatively narrow and somewhat permeable plantings, involving one to six rows and not too dense at the ground line, may lodge as much as 60 to 80 percent of the snow on the fields (Williams 1949) (fig. 6). This, cited as an example from a larger group of samplings, is equivalent under heavy snowfall conditions to as much as 17 acre-feet of water stored on the fields by a ½-mile-long shelterbelt of six rows. Potter et al. (1952) found water content of dense snowdrifts near shelterbelts in the Northern Plains to be 30 to 40 percent on a bulk density basis. Wider and denser planting, i.e., seven or more rows that are dense near the ground line, may retain much of the snow in the shelterbelt itself (fig. 6). Such retention benefits growth of trees but may reduce maximum crop-yield benefits.

Extremely deep snowdrifts that occur in some years on agricultural fields near dense shelterbelts tend to prevent uniform and early surface drying of the land, and the plowing, cultivation, or seeding of the narrow band of excessively wet soil near the belt may be delayed.

Often there is a substantial recharge of soil moisture due to melting of snow trapped by shelterbelts, especially in the northern half of the Great Plains. This effect may extend a considerable distance to leeward, as noted earlier. The moisture depletion caused by previous land use

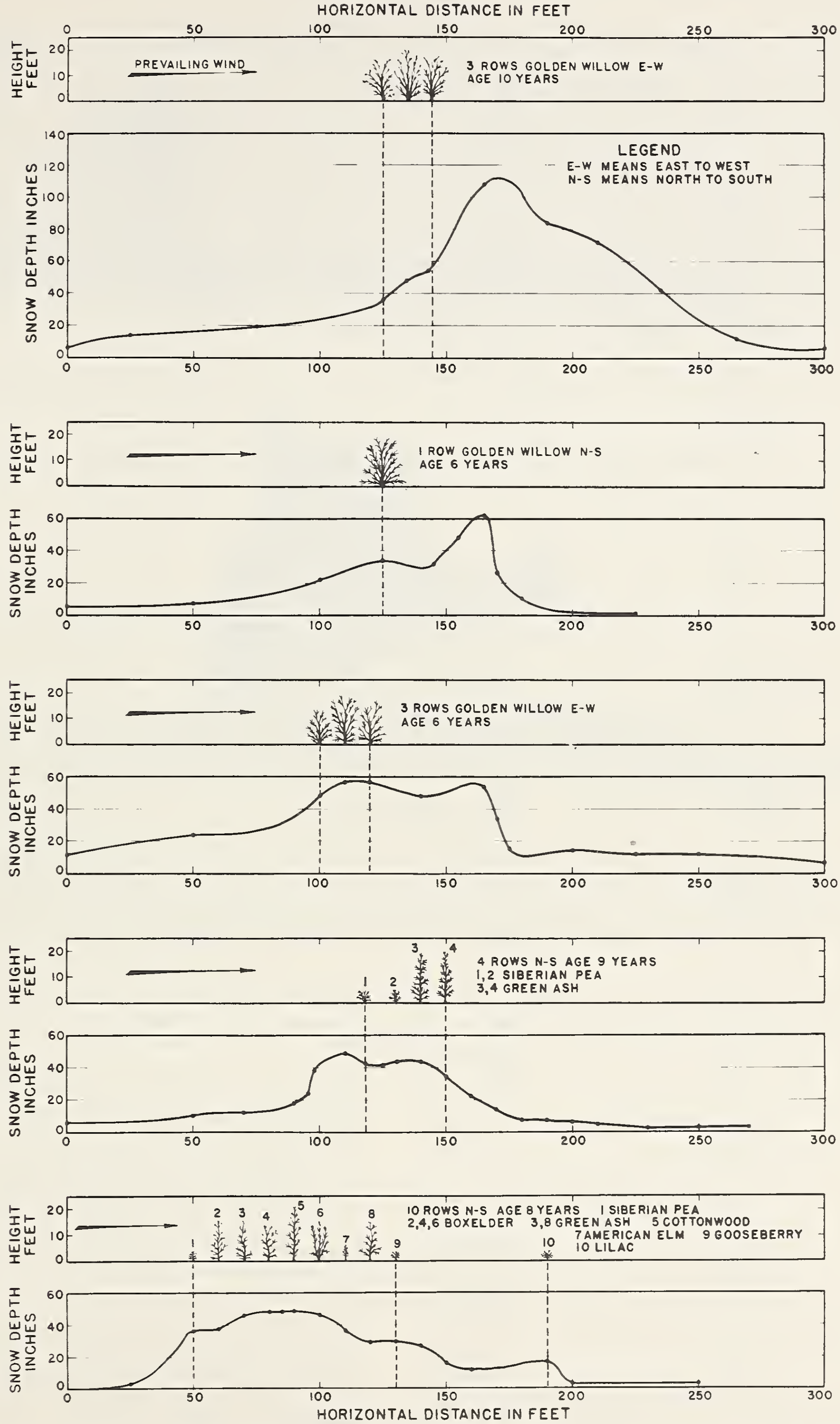


Figure 4.—Snow profiles observed near shelterbelts with one or more rows of dense twiggy shrubs on the windward side, North Dakota.

641754 O—62——2

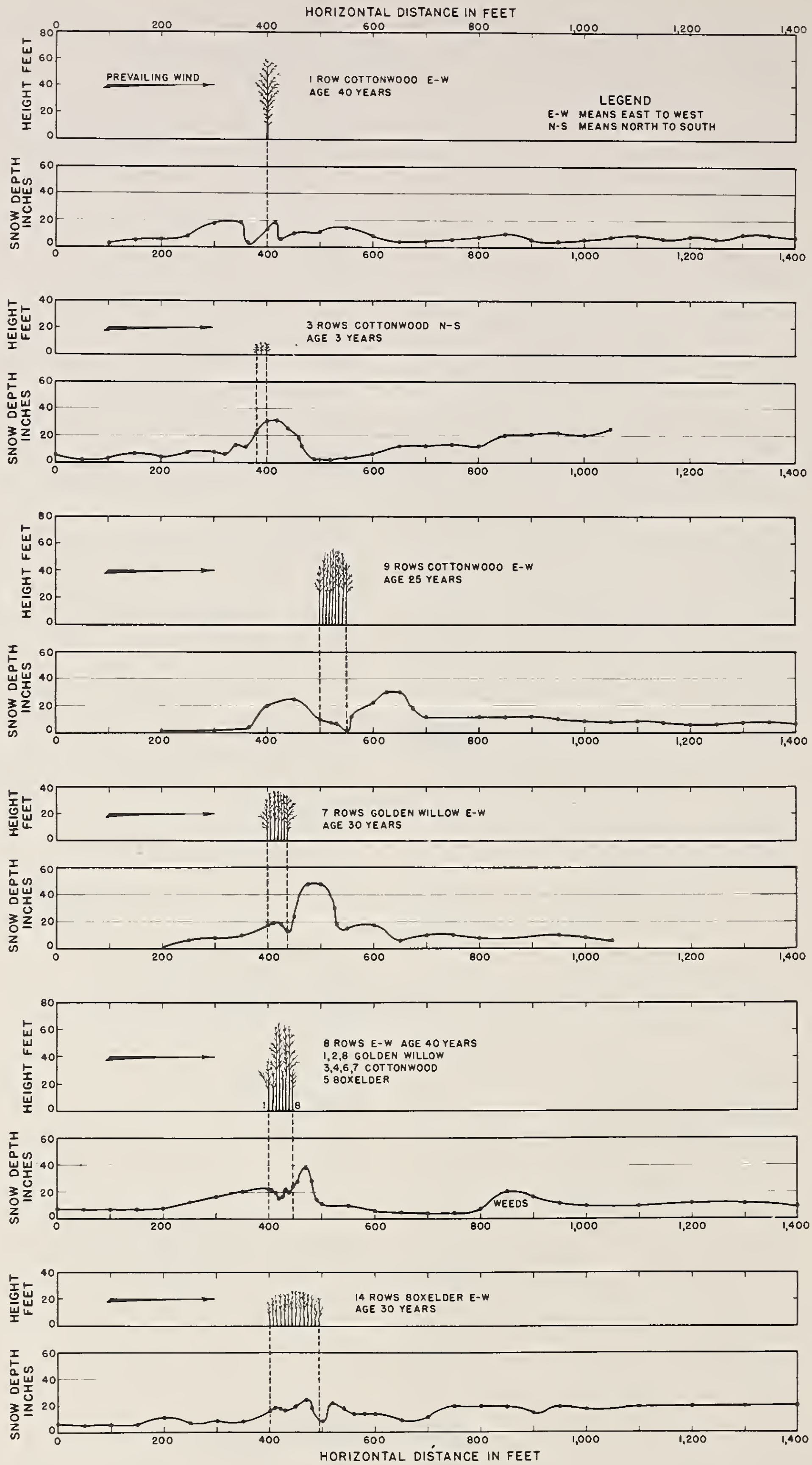


FIGURE 5.—Snow profiles observed near permeable shelterbelts devoid of shrub rows or dense limby growth near the ground line, North Dakota.

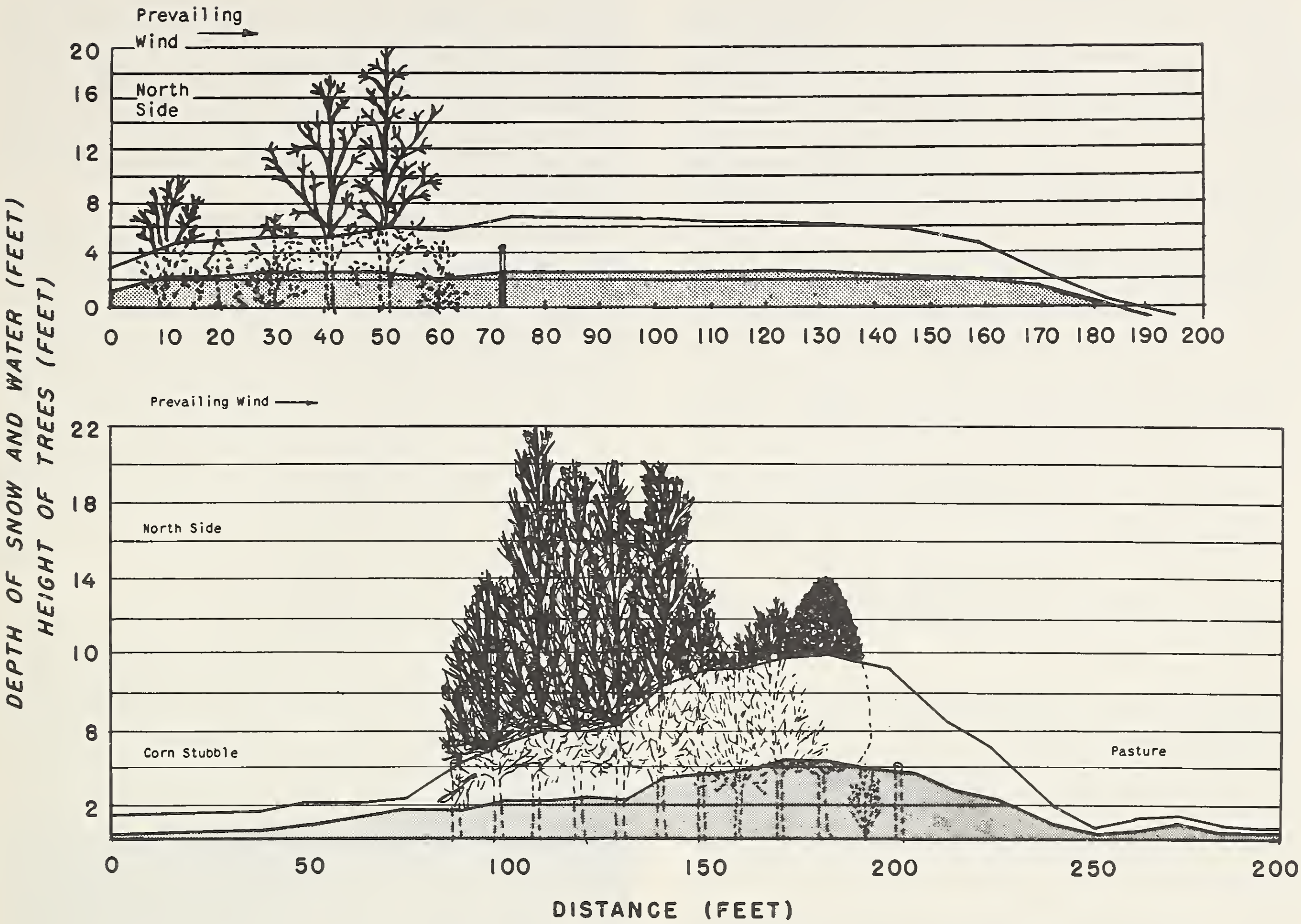


FIGURE 6.—Snow profiles (top line in each graph) near two shelterbelts of different density and width, O'Neill, Nebr., March 2–3, 1949. The lower line in each graph represents the water content of the snowpack. *Top*, A moderately permeable planting of 6 rows deposited about two-thirds of the snow on the nearby agricultural field. *Bottom*, A very dense 10-row shelterbelt deposited most of the snow in the belt itself, leaving less for soil moisture recharge on the nearby field.

may have a marked effect on the recharge observed at any specific time. An example of soil moisture as related to snowmelt is provided by early spring observations in and near a three-row east-west shelterbelt in Nebraska (fig. 7). This is a sample from one of 63 separate soil-moisture transects taken in a wide variety of belt widths, densities, and geographic locations. The asymmetrical pattern of overwinter soil moisture recharge, especially marked in the surface 2 feet of soil, is a result of the snow drifting pattern (Stoeckeler and Dortignac 1941, Potter et al. 1952, and Staple and Lehane 1955).

The asymmetrical pattern of springtime soil moisture on transects at right angles to shelterbelts is a common characteristic. It has also been observed in depth of frost penetration (Stoeckeler and Dortignac 1941). Even in areas with little or no snowfall there are reports of somewhat greater soil moisture at certain periods, especially in spring or early summer, on the lee side of shelterbelts (Catrina and Marcu 1955) owing to reduction in evaporation and transpiration (Lupe 1954).

Over 7,000 soil moisture samples were taken on 63 transects in and near shelterbelts in the Great Plains from North Dakota to Kansas in the spring of 1936. In the top 4 feet of soil of a selected sample of 11 transects extending on both sides of the shelterbelt and limited to the Northern Plains, there was about 3.5 percent more soil moisture on an ovendry basis in the zone at 5 tree heights to leeward and around 2.5 percent more at 0 to 7 tree heights than in the zone at 10 to 20 tree heights to leeward, or as far as 170 feet. This additional moisture, equivalent to 1.4 inches of water and ready for use in spring growth of crops, is undoubtedly an important factor in improved crop yields near shelterbelts in the northern Great Plains.

Shelterbelts tend to prolong snowmelt on fields and reduce loss of snow by sublimation (Zykov 1951). They also tend to increase dewfall (Bodroff 1935, Steubing 1952 and 1954) and thus slightly improve growth conditions.

Shelterbelts are more effective in conserving a maximum of snow moisture when stripcropping

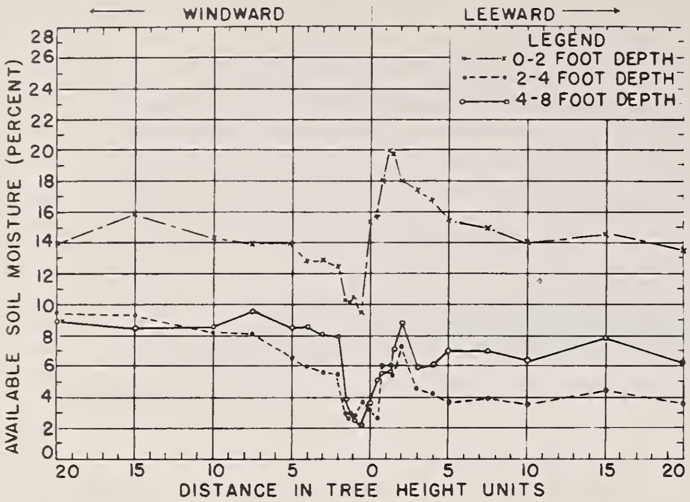


FIGURE 7.—Soil moisture in spring (1936) samplings at 3 different depths averaged for 3 transects taken at right angles to a 3-row shelterbelt. The shelterbelt, located in eastern Nebraska, was 25 feet high and east-west in direction, with a row of green ash on the north, a row of mulberry in the center, and a row of mulberry sprouts on the South side. The prevailing winter wind was largely from the north and northwest during the previous winter.

or when crops in buffer strips are used in adjoining fields (Kibasov 1955, Panfilov 1937).

Despite the recharge of soil moisture by shelterbelts, they often deplete soil moisture to a depth of 6 feet by midsummer (George 1943). Soil samples taken in the fall in Oklahoma showed a heavy depletion of subsoil moisture under the trees to a depth of 8 feet, and crops were affected in a zone at least 1 to 1½ tree heights on either side of the belt (fig. 8). Similar reports of strong depletion of soil moisture by shelterbelts have been made by other investigators (Masinskaja 1950, Stoeckeler and Bates 1939, Stoeckeler and Dortignac 1941).

Effect on Humidity

The effect of shelterbelts on relative humidity appears to be minor and local. Bates (1911) found no large difference due to the presence of shelterbelts, and Staple and Lehane (1955) found no measurable effect near one- to three-row plantings of rather low height in the Canadian Prairie Provinces. However, Bagley and Gowen (1960) in Nebraska, as well as some investigators outside of the Great Plains, have attributed modest increases in humidity to shelterbelts (Bodroff 1935, Bodrov 1936, Gorshenin 1941, Nägeli 1943 and 1946).

Effect on Temperature

The effect of shelterbelts on air temperature in the daytime has a distinct bearing on crop responses (Linde and Woudenberg 1951). These responses may be either favorable or unfavorable, depending on the crop, the location, temperature regime, orientation of the tree belt in relation to the sun, time of day, and the height and density of the tree belt itself.

In the central Great Plains, Bates (1911) found up to 9° F. greater fluctuation in temperature near shelterbelts than in the open, and in a later study (1944) under windy conditions he found a 1° increase 70 feet to leeward of a wide belt in daytime. An increase of 5° to 6° about 4 inches above ground has been recorded in the Netherlands (Linde and Woudenberg 1951).

In Kansas, near a 10-row, east-west shelterbelt, moderately dense at the lower level, Woodruff et al. (1959) observed as much as a 5° increase in daytime temperature at 2 H to leeward (north), normal temperatures at 3½ H, and as much as a 3° to 5° decrease in the zone between 6½ and 12½ H. At night, temperatures increased by about 1° out to 20 H in this zone, 2 to 3 feet above the ground.

The midday heat increase is less near permeable shelterbelts than near fairly dense plantings (Matiakin 1937). The latter cause air stagnation and hence more heating out to about 3 H. Bates (1911) observed a heat buildup also on the sunny windward side of Nebraska windbreaks.

F-432415-416

FIGURE 8.—Cotton growing on the north side of a 5-year-old, 19-foot-high shelterbelt in Caddo County, western Oklahoma. *A*, Strong depression of growth in the 5 rows nearest the shelterbelt and moderate suppression in a few rows beyond that. Man at right is standing in the 9th row. *B*, Growth in the zone of protection beyond tree roots. The men are standing in the 9th and 30th rows.

Heat increases near shelterbelts give variable responses in crops. In northern cooler latitudes, as in the Dakotas, the increase appears to favor heat-demanding, late-maturing crops like corn, although the zone of optimum development for corn is considerably farther south. On the other hand, it appears to penalize growth of corn on the south and west sides of shelterbelts in southern latitudes where there is ample heat under normal summertime conditions; here, corn on the sunny side of shelterbelts tends to burn in a zone out to several tree heights. With early-maturing crops, such as small grains, the heating effect of shelterbelts appears to increase growth rate in late spring and early summer when moisture conditions are favorable.

Reduction of Wind Erosion

Wind in the Great Plains often attains sufficient velocity to cause substantial soil erosion. Sandy soils move readily when wind speed 6 inches above ground attains or exceeds 11 miles an hour (D'yachenko and Zemlyanitski 1946). This is equivalent to a velocity of about 14 miles an hour at a height of 4.5 feet. Winds exceeding these velocities are common in the Great Plains (Bates 1935 and 1945).

Erosion depletes soil productivity. In addition, blowing soil may injure or cover up the young seedlings, thus reducing the stand and ultimately the crop yield. A combination of shelterbelts and stripcropping offers maximum prospect of soil erosion control on unstable soils.

Soils with 80 percent or more of fine sand are highly erodible (Chepil 1953a). The relatively high organic matter content of the Great Plains soils accentuates their susceptibility to wind erosion (Chepil 1954).

Effect of Shelterbelts on Crop Yield

Shelterbelts have been planted for the protection of crops and cropland for more than 50 years. Determinations of their effectiveness have been reported in the literature for approximately that period. Most of the research and experience in North America is directly applicable to conditions in the Great Plains. That from other parts of the world has less direct bearing but may help bring a fuller understanding of shelterbelt crop protection values in this country. Selected items from the literature outside North America are reviewed below, followed by fuller treatment of North American publications.

Observations Outside North America

In Germany, Bender (1955) found increased production of small grains ranging from 6 to 19 percent for the entire area between parallel 33-foot-wide shelterbelts 20 feet high and spaced 656 feet apart; increases in hay were 8 percent, in sugar beets 16 percent, in potatoes 12 to 16 percent, and in green beans 57 percent. The soils in this case were sandy and subject to wind erosion. Somewhat similar results were reported by Kummer (1955) and Thran (1952); Bülow (1951) reported increases of about 30 percent in crop yields protected by trees.

A report (Soegaard 1954) from the Jutland Peninsula of Denmark for narrow shelterbelts (mostly one or two rows) shows gains of 11 to 19 percent for small grains for the area between shelterbelts, 16 percent for potatoes, 23 percent for sugar beets, and 21 to 24 percent for fodder crops such as alfalfa, clover, and grass. Sørensen (1952) indicated that 10 percent is probably an average gain for most crops in Denmark in the area between shelterbelts.

In the Netherlands, Rhee (1957) reported that the yield of pears and apples increased noticeably up to 12 tree heights on the lee side of shelterbelts. Tree plantings have also been used in that country to reduce wind erosion on fields of flower bulbs (Linde 1948).

Wheat yields in Italy improved about 18 percent in a zone between 20 to 275 feet as a result of protection by 16- to 23-foot-high shelterbelts (Pavari and Gasparini 1943).

In Russia, Gorshenin et al. (1934) indicated that expected crop increases on land between shelterbelts is 20 percent for summer wheat, 56 percent for winter wheat, 26 percent for rye, 48 percent for barley, 100 percent for brome, and 203 percent for alfalfa. They found that in years of abundant precipitation oat rust tended to be more prevalent in protected than unprotected fields. The excellent response of forage crops to shelterbelt protection was also cited by Suss (1932) for brome, and by Ignatiev (1940) for alfalfa and crested wheatgrass, when hay yields were on occasion doubled. Shaposhnikov (1946) found yield of clover hay increased by 39 percent.

Suss (1935) and Karuzin and Shestoperov (1936) reported that in years of favorable rainfall small increases in crop yield of summer wheat, barley, and oats usually amounted to 10 to 15 percent; in years of moderate drought, 50 to 60 percent; and in severe drought, often 100 to 150 percent. Winter wheat showed even more contrast with values of 20, 100, and 400 percent. Because yields were low in drought years, the large percentages represent comparatively small additions to total production.

Vegetables in the U.S.S.R. (Suss 1935) on the average showed a much higher response to shelter-

belt protection than did the small grains. For instance, yields of cucumbers, carrots, and potatoes approximately doubled in shelterbelt-protected areas, and tomatoes and beets increased by about 70 percent. Approximate yields in unprotected fields for the cucumbers, tomatoes, and beets were 1,450, 1,380, and 1,270 pounds per acre.

At Gussel Experiment Station near Saratov, sampling of summer wheat near 7-year-old shelterbelts that were about 10 feet high indicated that approximately 7 years were required for annual crop increases to offset annual losses on space occupied by the trees or sapped and shaded by them (Gorshenin et al. 1934).

Similar data for the Krasnokutsk Agricultural Experiment Station (Gorshenin et al. 1934) indicated the need of restricting the amount of land actually devoted to shelterbelt plantings. For instance, in one of the experimental areas where 14.3 percent of the gross land area was occupied by 10-meter-wide shelterbelts with 60-meter-wide fields between, protective plantings had not paid for themselves in terms of actual increase in three varieties of wheat (pooled results) even by the end of the seventh year after planting. At that time the total net crop yield, adjusted for crop area lost to shelterbelts, was still 1.5 percent less than yields for unprotected areas. In the same study area, rye still showed a net loss in production by the end of the eleventh year.

Crop yields are more likely to show a reasonable net gain when narrow shelterbelts, occupying as little as 2 to 5 percent of the gross land area, are used. A network of plantings occupying 2.64 percent of the gross land area of Nansen State Farm near Arkadek in the U.S.S.R. was reported by Matiakin (1934) to have been effective in improving crop yields, even with the data adjusted for the space occupied by the trees.

Winter wheat on fallow land had a 6.9 percent net increase over the unprotected yield of about 1,140 pounds per acre; oats showed a 4.1 percent increase over the normal of 1,150 pounds per acre in unprotected situations; hay (vetch-oats) increased 31.4 percent; and millet and potatoes each 65.2 percent. Hay yields in unprotected areas were 1,240 pounds per acre and millet 400 pounds. Two crops showed no increase, i.e., spring wheat with a 0.5 percent loss and rye on fallow land a 10.6 percent loss. Perhaps most striking in the above data is the minor response to shelterbelt protection of small grains compared with hay crops, potatoes, or millet.

Panfilov (1932) cited a similar strong response in millet. Gordienko (1953) reported shelterbelts as especially effective in increasing yields of winter wheat—sometimes a twofold or threefold improvement. Sokolova (1937) also documented the favorable response of vegetables and winter wheat near shelterbelts; winter wheat showed a markedly greater response than summer wheat.

Russian investigators, Sokolova (1937) and Karuzin and Shestoperov (1936), have pointed out a marked variation in response of varieties of a specific crop to shelterbelt protection.

Sampling techniques and methodology of study noticeably affect the results of shelterbelt evaluation. For instance, Olbrich (1949) visited the Ukraine in 1943 near Vladimirovka and carefully sampled crops on contiguous 10-meter-square plots on transects at right angles to parallel 36-foot-high shelterbelts spaced mostly 39 to 46 tree heights apart. He observed considerably lower gains in crop yield on fields between shelterbelts than those generally reported by Russian investigators. This was especially true for hay, sunflower, and potatoes, and to some extent for small grains such as rye and oats.

Best gains near north-south shelterbelts were observed in soybeans and barley (25 and 27 percent, respectively); sunflower had a gain of 18 percent, rye 17 percent, oats 14 percent, and hay 4 percent. Potatoes between north-south plantings had a gain of 9 percent and between east-west shelterbelts a loss of 10 percent. The yield curve for a field of oats about 984 feet wide, between parallel north-south shelterbelts from 32 to 36 feet high, showed peak yields at 4 to 7 tree heights and some benefit to 18 tree heights east of the westerly planting. Peak yields were observed at 2 to 5 tree heights west of the easterly shelterbelt, with the influence extending to 9 tree heights. The effects of an individual shelterbelt extended for a total distance of 27 tree heights on both sides combined.

Panfilov (1932) ascribed much of the favorable effect of shelterbelts to the trapping and holding of snow on agricultural fields. Shaposhnikov (1946) demonstrated maximum wheat yields in zones of maximum snow deposit by contour-planted shelterbelts, and Goviadin's (1933) observations were similar for alfalfa hay in a zone lying between 10 and 50 meters from the shelterbelts.

Matsui and Yokoyama (1955) reported that yields of rice in Japan on the leeward side of a shelterbelt of willow and ash 4 meters high were favorably affected in a zone between 1 and 15 tree heights. The increases above yields in the open for stations at 1, 3, 6, 9, 12, and 15 tree heights were 3, 33, 49, 33, 28, and 8 percent, respectively. At 0.5 H the yield was depressed 51 percent.

Because the soils, crops, climatological conditions, experimental procedures, and other factors are highly variable, only very general inferences may be drawn from the literature on observations outside of North America. The following conclusions appear warranted:

1. Because of the effect shelterbelts have on the basic factors of environment, they can be expected to influence yields of most crops.

2. The kind of crop has a great deal to do with the effectiveness of protective plantings.

3. Relative effects expressed as percentages tend to be greater in years of climatic stress, although yield in absolute terms may be influenced to a greater extent in good years.

4. Shelterbelts occupying a reasonable percentage of the area (probably 3 to 5 percent) cause an increase in total crop yield. However, after the optimum percentage is reached, crop increases fail to compensate for additional area in trees.

5. The zone of influence on crop yield generally extends to leeward a distance approximately 20 times the height of the trees, with maximum effect occurring within 10 tree heights. Some crops are influenced to the windward side.

Past Observations in North America

Many farmers interviewed in plains areas of the United States and Canada consider that shelterbelts increase crop yields. In a South Dakota opinion survey of 331 farmers (Ferber et al. 1955), 83 percent said that crop yields were increased. Estimated increases were 2.3 bushels per protected acre for wheat, 4.3 for rye, 6.7 for corn, 7.4 for barley, and 80 bushels for potatoes. For corn silage the increase was 3.5 tons per acre and for alfalfa 0.56 ton. These estimates apply to the land devoted to agricultural crops with no allowance for space occupied by the tree belt. The average estimated distance to which crop growth was benefited on each side of the belt was around 330 feet.

Shelterbelts were rated as valuable in reducing wind erosion, fallen stalks in corn-borer infested land, and damage to crops by storms; in protecting flax from freezing in late spring; and in increasing estimated sale value of farms by about $7.50 per acre.

The conclusion of a Canadian opinion survey about shelterbelts in Manitoba, Alberta, and Saskatchewan was that tree belts have a favorable effect on crops to a distance of 230 feet (Edwards 1939).

In the United States, the earliest studies of shelterbelt effects on crops were made by Bates (1911) in the central Great Plains. He found that near a 38-foot-high dense grove of mixed tree species in Nebraska corn yields increased by 9.2 bushels per acre to a distance of 10 tree heights and 18 bushels in the zone of maximum protection. The gain was equal to as much corn as could be grown on an unprotected area twice as wide as the height of the trees.

For some studies of corn yield in Kansas and Nebraska on the north side of protective plantings varying from 22 to 60 feet high, Bates reported crop increases equivalent to what could be grown on an area of 1.03 to 1.93 tree heights. The benefits on the south side of four osage-orange hedges were not as great as on the north, but both together showed a net increase equal to 1.9 times the height of the trees. Corn crops protected on the east or west showed no net gain. On the north side of a tall cottonwood grove he observed a maximum 95-percent increase in weight of corn fodder and a 38-percent increase in weight of ears.

Wheat and other early grains showed less response than corn to shelterbelt protection (Bates 1911). In a wheatfield north of a maple grove, there was a considerable gain at 1.75 to 5.0 tree heights. The maximum was 10 bushels more than the normal 15-bushel unprotected yield. This gain, however, was almost offset by the loss due to sapping and shading; yields were adversely affected to a full tree height or more on each side of the shelterbelts.

Bates (1911) also cites the value of tree plantings in increasing yields of apple orchards in eastern Nebraska. Well-protected orchards had an average yield of 4.9 bushels per tree, while unprotected orchards yielded only 0.25 to 0.75 bushel per tree. He placed the average value of a shelterbelt in a critical year (1908) as at least $80 per acre on an area 10 tree heights wide.

In this early study (Bates 1911), the loss of crop yield due to sapping and shading was considerable at ½ tree height, and normal yields were attained only at about 1 tree height for most species. Near osage-orange hedges the zone of depressed yield was a full 2 tree heights and occasionally 3.

Crops in eastern Kansas, Nebraska, and South Dakota were badly damaged in 1935 by heat and lack of rainfall. Benefits of shelterbelt protection were at a minimum under these conditions. Nevertheless, the gains in wheat and corn yields in protected fields paid for the land occupied by trees, except where the crop was completely destroyed (Bates 1944).

In the same year the gain in one field of alfalfa was equivalent to the yield on an unprotected strip equal to 4 tree heights. In a second field the gain on the south side of a single row of 60-foot-high cottonwoods was equal to the yield on a strip nearly 100 feet wide.

In a summary of the effect of shelterbelts on wheat and corn yields during 1935–41, Bates (1948a) noted greatest response to shelterbelt protection in North and South Dakota on the south side of east-west plantings. The gain was equal to the yield on a strip the length of the belt and 70 feet wide. To the north, the equivalent strip was 28 feet wide. There was no additional yield to the west of north-south shelterbelts, but to the east it was equivalent to the yield of a 33-foot strip.

Farther north in the Great Plains, near Aneroid, Saskatchewan, Staple and Lehane (1955) studied wheat yields for several years between north-south parallel, single-row, 15- to 19-year-old Caragana hedges. These had been planted at intervals of about 445 feet and averaged 7 to 9 feet high. The average annual increase in yield was 0.7 bushel per acre, and maximum increases of 5.0 and 6.5 bushels per acre were recorded at 2 to 5 tree heights from belts. The average increase includes allow-

ance for the space occupied by the hedges or sapped and shaded by them.

Increased yields above the 20.5-bushel average at field midpoints were due largely to snow trapping and its recharge of soil moisture in spring. The gain in crop yield was greatest in years of abundant snowfall and years with low summer precipitation. Average annual precipitation in the study area is about 13 inches. Staple and Lehane concluded that shelterbelt influence is more striking in dry than in wet years. The areas of increased yield remain about the same, but relative yields are greater near the shelterbelt, especially within 4 to 5 tree heights.

In Wyoming (Quayle 1941), yields of crested wheatgrass immediately north of single-row 18-foot-high shelterbelts were double those at a distance of 150 feet in the drought year of 1938. For the 5-year period 1937–41, the average yield was 1,209 and 887 pounds per acre, respectively, for the two locations.

Similar response of a forage crop was reported by Trenk (1948) at Hancock in central Wisconsin. On the protected (east) side of eight rows of conifers 17 feet high, hay (mixed alfalfa, timothy, and red clover) showed about 37-percent increase in yield at 20 to 120 feet from the trees or between 1 and 7 tree heights from the dense barrier.

Orchards seem to be especially responsive to the protection of shelterbelts. Apparently the fruit sets better, conditions are more favorable for pollination, spray covers the trees more evenly, and there is less dropping or rubbing of fruit (Stoeckeler and Williams 1949).

One of the most convincing studies of positive shelterbelt benefits was made by Metcalf (1936) who showed the net advantage of tall one- or two-row eucalyptus plantings to be about $92 per acre per year in citrus groves. The benefits were largely in terms of reduced fruit drop and less scarring by rubbing, which degrades the market value of fruit. A spacing of 300 to 400 feet between eucalyptus plantings was recommended for maximum protection of the citrus crop.

SCS–79500

FIGURE 9.—A network of narrow shelterbelts protects orchards (at right) as well as grainfields near Blair in western Oklahoma.

In Lower Michigan, single rows of white pines are used near cherry orchards to keep sprays from drifting off the field. Shelterbelts have also been used to protect orchards in the Great Plains area (fig. 9), and they are considered beneficial.

Vegetable crops have also benefited when protected from wind. Bagley and Gowen (1960) recorded a yield of 16 tons per acre in a harvest of early tomatoes that were protected from both north and south by 7-foot-high fences; unprotected areas yielded 10 tons per acre. For the entire harvest, the yield was 16 percent higher under shelterbelt protection. Snap beans showed a 37-percent increase.

Shelterbelts have other agronomic values besides increased crop yields. In Oklahoma they reduced outcrossing of corn as much as 50 percent and had some effect to a distance of 15 rods (Jones and Brooks 1952).

Dambach (1948) reported many beneficial insects and fewer injurious ones near shelterbelts than in areas without protection.

Crop-Yield Study in the Great Plains, 1935–41

Methods

During 1935–41 the effect of shelterbelts on crop yields in the Great Plains region was studied by the Lake States Forest Experiment Station. These studies were confined largely to small grains, mostly wheat (some rye, barley, and oats were included) and corn. Some sampling was done in cotton and alfalfa.

Test fields were located in North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas, in a strip between the 98th and 100th meridians of longitude. In the four northern States the chief crops harvested were wheat and corn. In the two southern States the sampling was confined to cotton. A single crop grown at least 20 tree heights from the shelterbelt was required.

The shelterbelts bordering the selected fields were not part of a closely spaced network of parallel and cross belts but were isolated and invariably one-half mile or more from the nearest shelterbelt. They were of good continuity (without gaps) and of reasonably good density, generally 60 percent or more, based on ocular estimates. Fields had a minimum length of at least 20 tree heights. The number of tree rows usually ranged from 7 to 30 with a width of 50 to 250 feet; some narrow 1- to 6-row belts were also studied. Height of the trees usually ranged from 25 to 50 feet, and the average height was about 40 feet.

All fields were on land owned by farmers who gave investigators permission to do the crop sampling and were able to furnish background data on the crops and fields. Very few of the fields were sampled more than once during the entire study.

The crop-sampling techniques were worked out in consultation with agronomists in the Great Plains and with statisticians. The crops were harvested on predetermined small plots or rows located along lines at right angles to the shelterbelt. Intensity of sampling increased during the study.

It should be noted that in any study involving crop sampling near shelterbelts, large numbers of fields must be sampled to smooth out the tremendous variation in yield for a particular crop. Variation on individual fields comes from many sources, including inherent soil fertility and soil moisture differences, patchwise or zonewise insect and disease damage, and mammal and bird damage. Sample plots were located far enough away from ends of shelterbelts so that practically all of the samples were enclosed by a line 45 to 60 degrees from the end of the shelterbelt. An attempt was made to keep transect lines at least 20 tree heights away from the right-angle intersection of two tree belts.

A diagrammatic outline of the standards for sampling is shown in figure 10. Sampling stations were fixed in terms of effective tree heights. Usually three sample plots were harvested at each of the following multiples of tree heights: 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.40, 2.80, 3.20, 3.60, 4.00, 4.50, 5.0, 6.0, 7.0. 8.0, 9.0, 10, 12, 14, 16, 18, and 20 H. Where space permitted, samples were carried out to 29 H. Hence, each single transect line required at least 23 samples, or 69 as a minimum per field. If there was a harvestable crop as close as 0.5 H, it was harvested. The yields obtained from these samples were used to estimate the yield for the entire field.

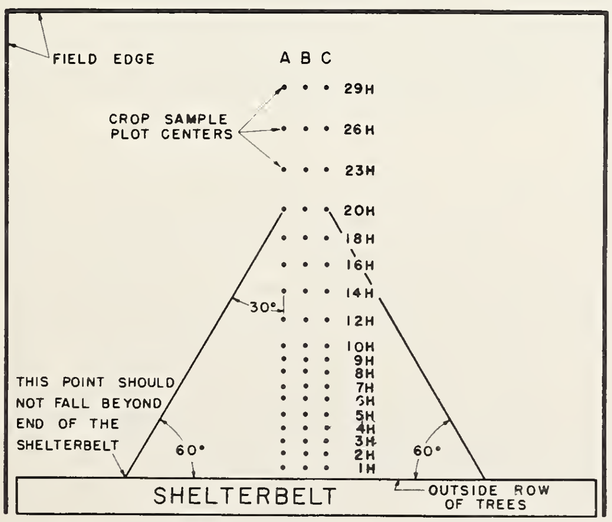


Figure 10.—Scheme of crop sampling on transects.

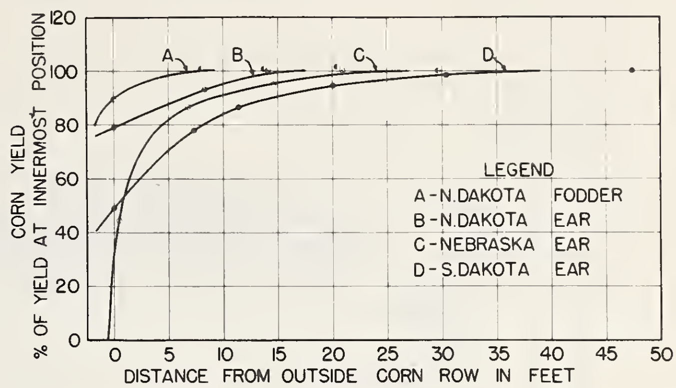


Figure 11.—Loss in yield of corn near a field edge not adjacent to a shelterbelt.

Grain samples were harvested by clipping them at the ground line, placing them in labeled bags, and threshing them out at the nearest agricultural college or nearby substation. Weight of straw was recorded as well as that of the cleaned grain.

During the first 4 years of the study, no adjustments were made for losses in yield that occurred at field edges where a narrow band is normally left unplanted. This unplanted margin ranged from 1.0 to 6.5 feet average width, by State. Corn sustains an additional loss due to lower yields near field edges (fig. 11), but wheat apparently is not affected.

Obviously these field-edge losses, which would occur even if the shelterbelt were not there, should not be marked as a penalty against the shelterbelt. Therefore, from 1939 on, a "normal" field-edge correction was used in all tabular or graphic presentations involving yields in terms of bushels or tons per acre.

All crop yields were expressed in terms of air-dry weight. Corn was weighed and shucked and samples taken for moisture content. Cotton was picked as often as necessary in order to obtain a complete harvest. It was ginned and its weight and the weight of the cotton seed were kept separate. Fodder corn was harvested and weighed and the moisture content determined.

Graphs were made, showing yield data for individual fields plotted over tree-height distances from the shelterbelt. The gains in the favorably affected zone and the losses in the area of competition were planimetered separately, and the net benefit for the cropped land was computed in terms of pounds, bushels, or tons.

The calculated "normal" or check yields—that is, of areas not affected by the windbreaks (usually beyond 15 tree heights)—are as follows:

Crop	*Yield per acre*	*State*
Small grains (bushels)	18	North and South Dakota.
Do	17	Nebraska and Kansas.
Fodder corn (tons)	2. 4	North and South Dakota.
Ear corn (bushels)	34	Do.
Do	25	Nebraska.
Do	26	Kansas.

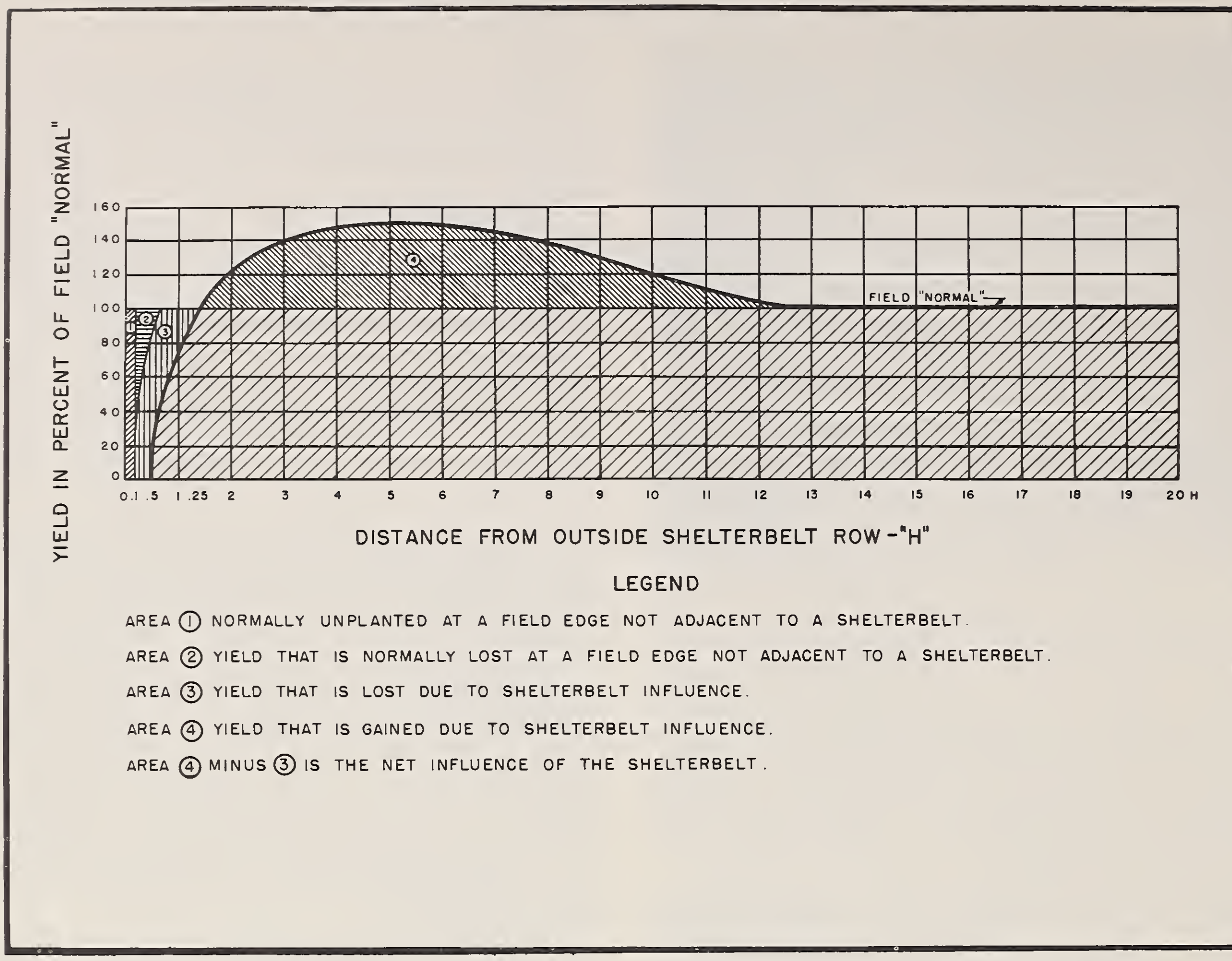


FIGURE 12.—Cross section of crop yield on a field under shelterbelt influence. H=1 unit of tree height, in this instance 40 feet.

The various components entering into the calculation of crop-yield effects on a field adjacent to one side of a shelterbelt are illustrated in figure 12.

Finally, summary graphs were drawn combining data for one or two States by crop and by orientation of the fields with relation to the shelterbelt. All small grains were combined to obtain a stronger sample. Wheat comprised about 80 percent of the total of all small grains.

In all the graphs showing yield for a specific crop in percentage relation to check plots beyond the influence of the shelterbelt, the yield data are based on measurements carried back to zero (0) tree height. This reference point was always directly in line with the outside row of trees or shrubs on that side of the belt including the entire zone affected by sapping and shading.

Response of Small Grain

Ninety-four fields of small grain were sampled. Yields in relation to shelterbelt orientation are given in figures 13 and 14.

In the Dakotas the net benefit from shelterbelts planted on the interior of fields appears to be about equal for north-south and east-west orientation. Yields were favorably influenced in all four positions relative to the protective plantings. Fields to the east of shelterbelts were benefited more than those to the west. This is attributed to the prevailing northwest winds during all but the summer months. In the winter more drifting snow is deposited on the east than on the west side of the trees.

In Nebraska and Kansas, only fields on the south and east of shelterbelts showed substantial benefit. Those on the south apparently were favored both by increased temperature for an early ripening crop and by deposition of snowdrifts during the winter on the south side of the trees. The increases to the east are attributed mainly to the increased moisture from drifting snow.

The Dakota samples were studied more intensively to bring out other relationships associated with total yield of grain. A comparison was made of the effect of north or south protection on yield of straw and test weight of grain (fig. 15). Peak production of straw occurred close to the trees. Apparently sapping and shading affect grain yields more than they do stem and foliage growth. For unexplained reasons, protection to the north favored the production of straw more than that of grain. Test weight[3] apparently

[3] Test weights for a value of 100, as used in figure 15, are 60 pounds per bushel for wheat, 56 for rye, 48 for barley, and 32 for oats. For example, wheat weighing 63 pounds per bushel has a test weight rating of 105.

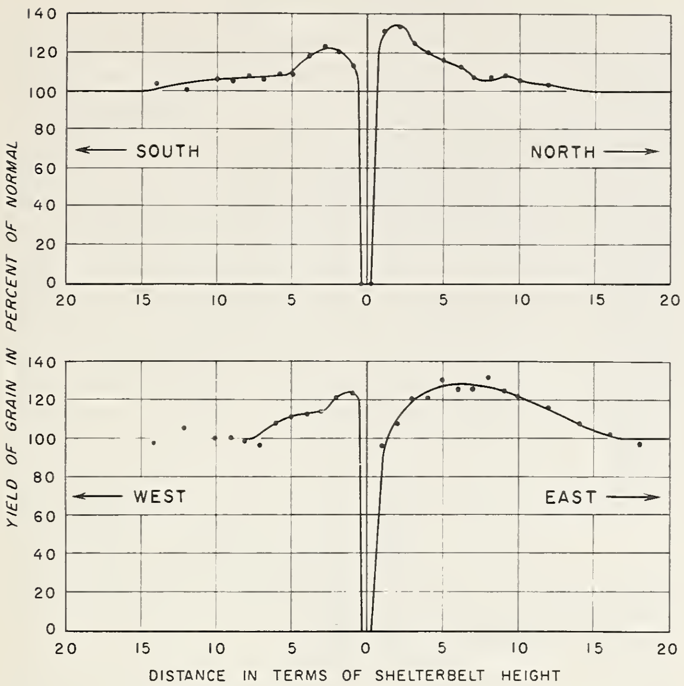


FIGURE 13.—Influence of shelterbelts in North and South Dakota on yields of small grains in fields lying to the north, south, east, and west of the trees. The curves are based on averages of 34, 12, 6 and 6 fields, respectively, for the four directions.

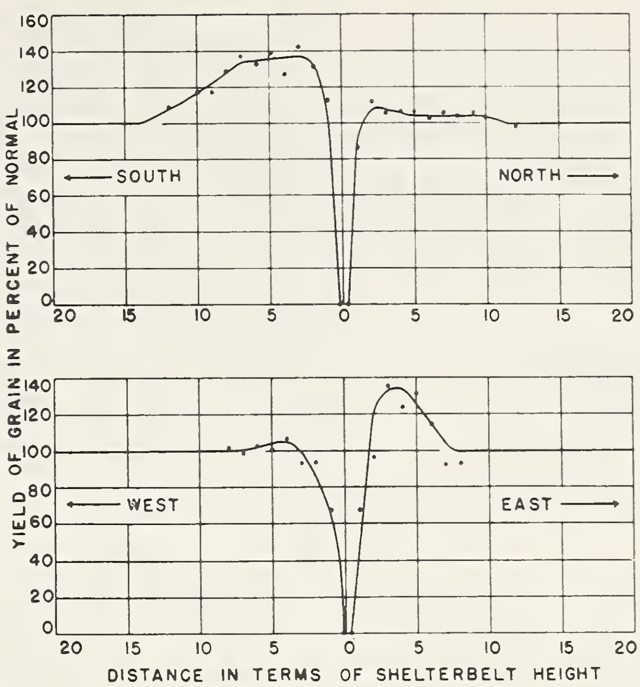


FIGURE 14.—Influence of shelterbelts in Kansas and Nebraska on yields of small grain in fields to the north, south, east, and west of the trees. The curves are based on averages of 18, 6, 7, and 5 fields, respectively, for the four directions.

benefited from protection. There was a small but consistent gain of about 2 percent on both sides of the trees to a distance of approximately 10 H.

The Dakota fields north of shelterbelts were separated into low- and high-yield classes for further comparison. Separation was based on normal unprotected yields greater or less than 140 percent of the 1927–38 State average for the crop. Thus the 34 fields were split into approximately equal groups—15 of high yield and 19 of low yield. The shelterbelts themselves had very similar average dimensions. Yields on the less productive fields were benefited much more than those on the more fertile ones, as shown in the tabulation and figure 16 on page 16. The greater gains for the less productive fields probably indicate more critical moisture relations there, which were improved considerably by shelterbelt protection.

The shelterbelts were of greater width than can be justified on the basis of increased yield. If yields for the gross land area were corrected for space occupied by the trees (as suggested in table

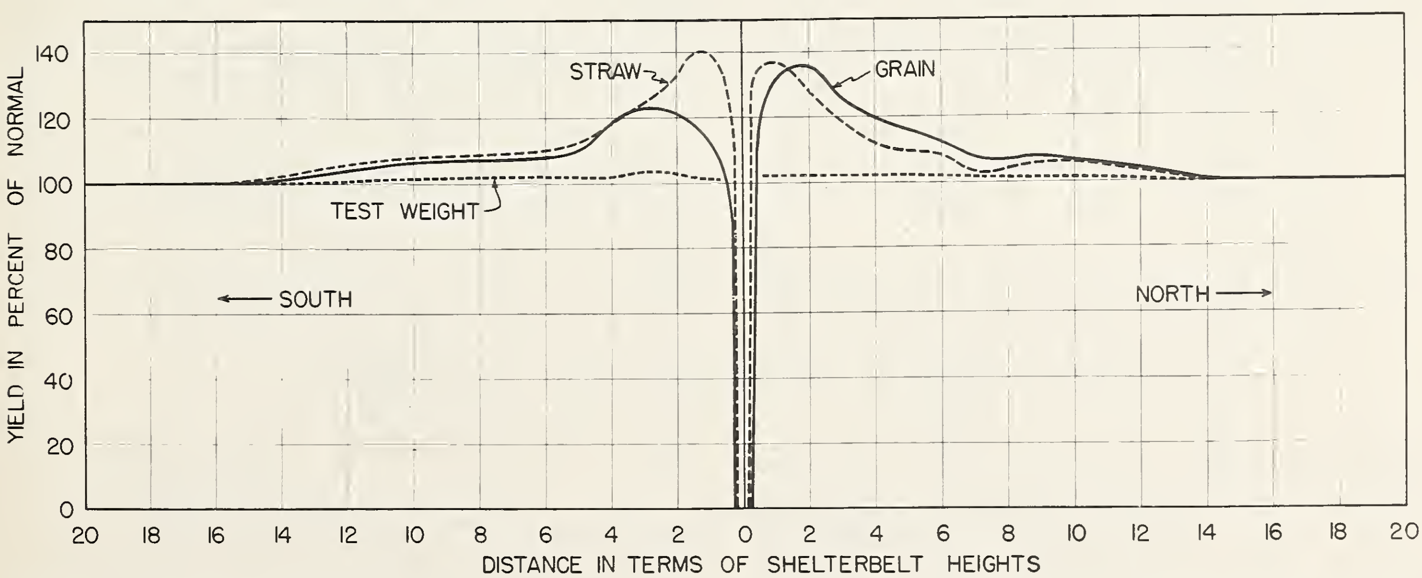


FIGURE 15.—Effect of shelterbelt protection on yield of grain and straw and on test weight of small grains in fields lying south and north of the trees, North and South Dakota.

	Fields north of windbreaks	
	High-yield capacity	*Low-yield capacity*
Average normal yield of small grain per acre for unprotected area [1] bushels	20.68	12.29
Average increase per acre on protected area to 14 tree heights from belt bushels	1.10	2.19
Average total increase in yield of small grain per ½ mile of belt [2] bushels	36.46	74.18
Average shelterbelt:		
Height feet	39	40
Width do	203	185
Density percent	73	68
Age years	50	47
Belt basis number	15	19

[1] Beyond the protective zone of the trees.
[2] Benefit from the belt in the field to the north; not a per-acre figure.

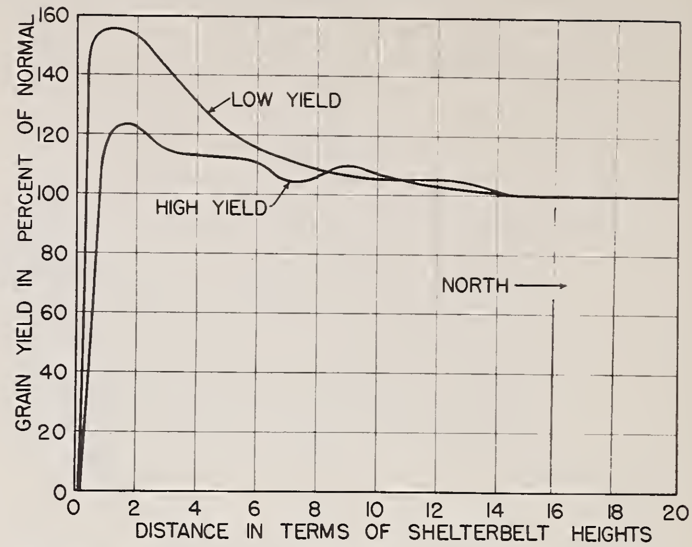


FIGURE 16.—Small-grain yield in percent of normal on high- and low-yielding fields located north of shelterbelts in the Dakotas, 1935–40.

1, p. 21), it is obvious there would be a net loss in crop yield for the gross area. At the time of the study, these wider tree belts were the only ones available in large numbers as study material. The important fact brought out is that crop response to shelterbelts may vary depending on the inherent fertility and moisture relations of the soil.

Response of Corn

To determine the response of corn to shelterbelt protection, 184 fields were sampled, almost half of them in Nebraska. Considering all field locations, ear corn responded more favorably to shelterbelts in Nebraska than in the Dakotas or Kansas (fig. 17).

Ear corn in the Dakotas showed substantial gains only on the fields south of windbreaks, apparently because of the beneficial effect of in-

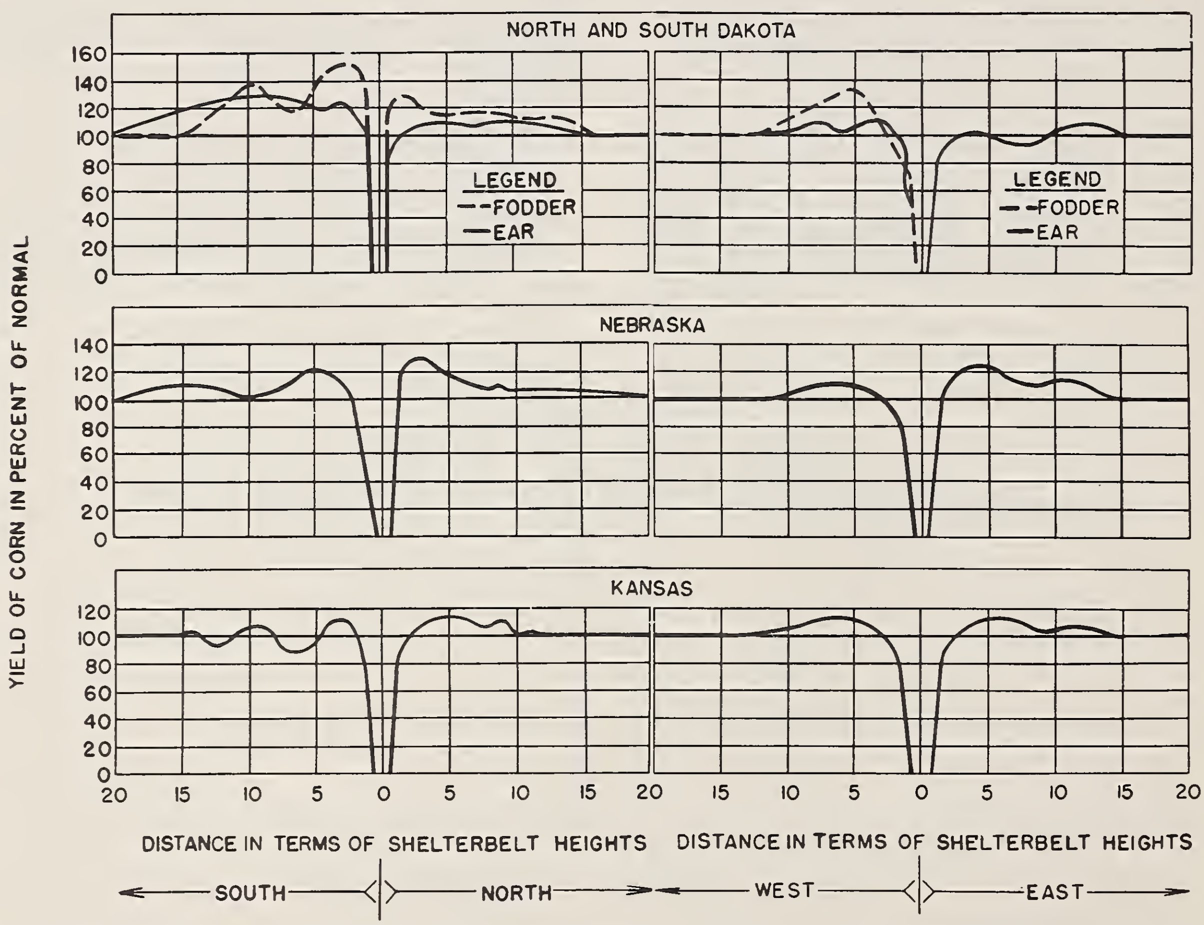


FIGURE 17.—Yields of corn in percent of normal, North and South Dakota, Nebraska, and Kansas: *A*, 77 fields to the north and 32 fields to the south of shelterbelts; *B*, 40 fields to the west and 35 fields to the east of shelterbelts.

creased air temperatures there (Bates 1911). Crops north and east of shelterbelts showed the least response.

Fodder in the Dakotas showed the highest average increases on the south fields but increases were substantial on west and north fields also.

In Nebraska, fields lying east of shelterbelts showed greatest response, with an increase averaging about 19 percent between 2 and 10 tree heights and some favorable effect extending to 15 tree heights. Fields north of shelterbelts rank next in gain, followed by those to the south and west. The response of corn to shelterbelt protection in Kansas was somewhat less than in Nebraska, but the ranking of fields from most favorable to least favorable was fairly similar. The Kansas and Nebraska data illustrate the effect of protection from hot dry summer winds.

A statistical test by analysis of variance, made on 27 separate Nebraska cornfields selected at random, revealed significantly beneficial increases in crop yield on 20 of these fields, no effect on 5 fields, and significant losses on 2 fields.

A rather striking feature of the corn yields is a decrease at around 6 or 8 tree heights on east, south, and north fields. This is believed to be due to downdrafts of wind that arch over the shelterbelt and strike the ground at that distance. It is surmised that late-maturing crops like corn are more likely to be adversely affected by these downdrafts than early-maturing crops like wheat; wheat has made most of its total growth early in the season before full leaf development, and hence density, of the shelterbelts. In any case, yield curves for wheat, an early-maturing crop, do not show this response pattern.

Response of Cotton

Eight fields of cotton in Oklahoma and Texas were sampled in 1940. Seven fields were north of shelterbelts and one was east. The young shelterbelts, planted in 1937–39, ranged from 9 to 17 feet in height and averaged 12 feet. Density in summer ranged from 50 to 75 percent and averaged 67 percent.

For each height station, cotton yields were determined on two 50-foot rows parallel to the shelterbelts. The rows were carefully staked at each end so that repeat pickings (usually four or five) would be made on the same rows. Picking extended from September 30 to December 30, 1940.

The yields of lint and seed obtained in all pickings are given in figure 18. Lint yields increased substantially to about 20 tree heights, with most of the benefit within 10 tree heights or 120 feet of shelterbelts. Peak production was reached at around 3 tree heights where yields were 46 percent above those on the unprotected parts of the field. The average increase in yield between 1 and 22 tree heights, based on the samples between 40 and 240 feet, was 23.3 percent.

Yields of cottonseed also increased to about 18 tree heights, or to a distance of about 216 feet (fig. 18). Peak production was attained at about 2 tree heights where yields were 50 percent above those on the unprotected parts of the field. The average increase in cottonseed yield between 1 and 18 tree heights was 27.2 percent, based on the samples between 20 and 200 feet.

After adjustments were made for losses due to the competition by trees as well as for the average unplanted field edge of 6 feet, the gain in lint yield in a field on one side of a shelterbelt was equal to the crop yield that could have been obtained on an unprotected 62-foot-wide strip. These limited data for cotton indicate that if shelterbelts are to justify themselves in increasing crop yield, they must be rather narrow plantings.

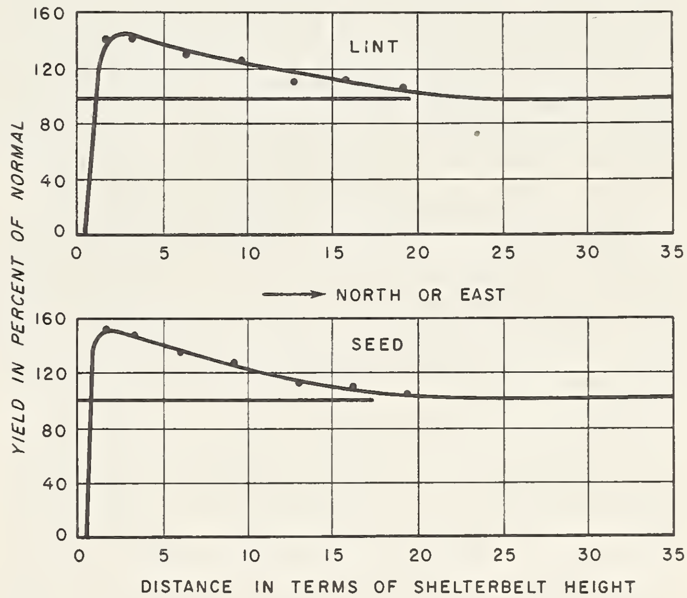


Figure 18.—Yield of cotton lint and seed in percent of normal. Fields were to leeward of eight southern Great Plains shelterbelts in Oklahoma and Texas.

Guides for Development of Shelterbelts

Variability in Protection During the Life of a Shelterbelt

The protection value of a shelterbelt ranges from zero at the time the trees are planted to a maximum when they reach full height and density. Establishment and early growth of the trees may take about 8 years. During this time there is not much protection, and the area occupied by the trees is lost to production. Then, crop gains gradually increase and counterbalance crop loss from the area occupied by the trees. Finally, there is a period of maximum effect when a shelterbelt makes its greatest contribution to yields. These three phases of shelterbelt development are illustrated in figure 19.

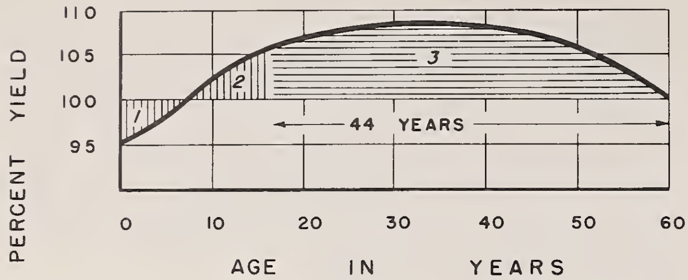


FIGURE 19.—Estimated long-range effect on wheat yields adjacent to a 40-foot-wide, 5-row shelterbelt having an effective lifespan of 60 years, with 44 years of net crop gain. The three periods represented are as follows: (1) early period of loss in crop yield, (2) period of crop gain offsetting losses in first period, (3) period of actual net gain in crop yield. The 100-percent value represents normal yield without protection of a shelterbelt.

The curve in figure 19 is based on actual crop yield data for small grains in the eastern Dakotas and is for only 44 years of an effective lifespan of 60 years for the shelterbelt. It was adjusted somewhat on the assumption that well-designed narrow belts give better deposition of snow on adjoining cropland and hence better crop yield than the rather wide belts available during this study. Giving due consideration to the space occupied by the trees and sapped and shaded by them, one concludes that for small grains the overall gain per annum for the entire lifespan of a shelterbelt would be in the range of 3 to 5 percent. Expressed in another way, gain in crop yield in the eastern Dakotas is calculated as being about 1 bushel per acre or slightly less for the gross land area in wheat that is protected by shelterbelts.

This figure is in close agreement with observations by Staple and Lehane (1955) in the Canadian Prairie Provinces. They found a 3.4 percent gain in wheat yields from shelterbelt protection. The gain was 0.7 bushel per acre for the gross land area. Average yield in unprotected areas was 20.5 bushels.

The belts in this Canadian study were only 7 to 9 feet high and were spaced somewhat too widely (454 feet apart or 64 tree heights) to have a maximum effect on wind reduction over the entire field area. They were, however, very effective in design as snow traps. Even at a closer spacing of about 200 feet, the actual increase in yields would probably not have exceeded 1.5 bushels per acre.

From data available for the Great Plains, it appears that yields of cotton or forage crops, including fodder corn, will show comparatively more response to shelterbelt protection than do the drought-hardy small grains. Also, there is some evidence that shelterbelts will have a greater beneficial effect on yield of crops planted on highly erodible sandy soils than on yield of crops planted on relatively stable soils where soil erosion can be controlled by stripcropping alone.

Figure 19 has other points of significance in the long-range, farm-management outlook for shelterbelts. Once a tree belt is established, a system of management to reduce the considerable period of comparative ineffectiveness that occurs in the belt's young as well as older stages may be desirable. One solution in multirow belts may be removal of some of the rows 10 years or more before their senility and then rejuvenation by coppicing in the dormant season. Or, these rows might be cut, treated chemically, and then replanted, with some root and top pruning of the nearest row of older living trees to reduce their sharply competitive effect.

Treatment of established shelterbelts should be done with the advice and guidance of technical men in Soil Conservation district offices or foresters in one of the State or Federal forestry agencies, since a number of technical considerations of the advantages and possible disadvantages of such treatment are involved. One disadvantage would be the reduced value of the belt as a shelter for pheasants and for beneficial, insectivorous birds. Another would be the possible impairment of its wind-reduction capacity or effectiveness as a snow trap protecting farmsteads or roads.

The other alternative to achieve better continuous protection of the land, and one more readily and safely applied in practice, is to use a rotation system on the shelterbelts. In such a system, one set of parallel one- or two-row belts would be planted at 20 to 30 ultimate tree heights apart, and then at midlife of these belts additional parallel one- or two-row belts would be planted at midpoint between the older belts to achieve a gradual overlap of the beneficial zones of influence. In this method, the original rows would be completely removed at the end of their lifespan and replanted, leaving the overall area temporarily under partial protection of the younger belts at 10 tree heights or more away on either side.

The growth rate and lifespan of the trees are primary factors in the timing and magnitude of their protection effectiveness and amenability to treatment. The species planted, the care the trees receive, and the quality of the site are all important. Research and experience have furnished some guidelines to proper selection of species in relation to soil, topography, and geographic location (George 1953, Hayes and Stoeckeler 1935, Read 1958).

Effect of Shelterbelt Density on Crop Yields

A separate analysis was made on the 1938 samplings in Nebraska to determine the effect of shelterbelt density on yield of corn in fields to the north. Data for 10 wide, dense broadleaf shelterbelts averaging 275 feet in width and 86 percent in density (expressed as percent of full foliage) and for 6 narrow shelterbelts averaging 11 feet in width and 52 percent in density were analyzed and plotted (fig. 20).

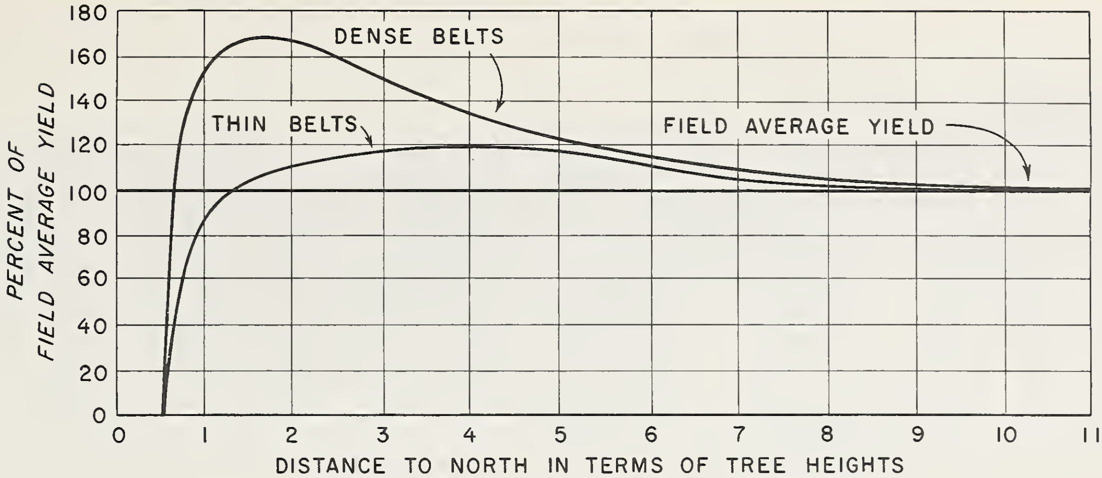


FIGURE 20.—Comparisons of 1938 Nebraska corn yields north of shelterbelts of low density (52 percent) and high density (86 percent).

The average increase was 19.0 percent for crops protected by dense plantings and only 2.6 percent for those protected by the less-dense shelterbelts as noted:

	Shelterbelt density	
	High (*86 pct.*)	*Low* (*52 pct.*)
Shelterbelts (number)	10	6
Fields north of belts:		
Average yield per acre on unprotected area (bushels)	27.2	31.2
Average gain to 10 tree heights[1] (percent)	19.0	2.6
Average benefit for ½ mile belt[2] (bushels)	180.72	11.74

[1] From edge of planting (zero H) to 10 H, considering only one side (based on values from curve).

[2] For the entire field area on only one side of the belt; not a per-acre figure.

If the corn yields were corrected for space occupied by the tree belts, the denser belts, which occupy an unduly wide strip of land, would of course not pay for themselves in terms of net yield. The data were limited by the type of belts available for study; narrow belts of good design were extremely scarce.

These observations emphasize that density of a shelterbelt can be a factor in crop response. The subject deserves much additional research, especially on younger shelterbelts of better design for which data were not available at the time of this study. In considering crop gains, however, which necessarily involves the space occupied by the trees, a fairly dense shelterbelt occupying a minimum width is the one most likely to provide reasonably good gains and some measure of wind-erosion control. Even one-row plantings might meet this requirement if composed of trees of unusually high density, such as conifers or mulberry, which were observed to be effective wind barriers in western Oklahoma (Stoeckeler 1945).

Comparatively narrow shelterbelts occupy little space, are easier to keep free of weeds, and, in areas of considerable snowfall, tend to deposit more snow on adjoining agricultural fields than do wide belts with a dense shrub row on the windward side. On the other hand, any mortality or failure of narrow plantings is certain to seriously curtail their effectiveness.

The natural density attained by shelterbelts is rather closely associated with the individual growth habits of a species (fig. 21). Single-row mulberry hedges often attain a summertime density of 70 to 80 percent. Single rows of osage-orange were found to average 52 percent. Boxelder plantings averaged around 66 percent in density, while cottonwood plantings, even if consisting of multiple rows, averaged only 39 percent because of open crowns and a tendency toward natural pruning from below.

Single-row coniferous plantings in areas of considerable snowfall may require light pruning of the lower branches to a height of about 3 feet to avoid deep deposits of snow and excessive wetness in and too near them. In some European countries judicious pruning is an important management procedure to regulate the density of broadleaf and coniferous shelterbelts and thereby achieve the desired pattern of snow distribution on nearby agricultural lands. Much is yet to be learned in this and other phases of shelterbelt management in the Great Plains.

Shelterbelt Width in Relation to Benefits to Small Grain and Corn

The data presented in this bulletin are for specific crop years, since very few fields were sampled more than once. They also represent crop varieties and farming practices of about 20 years ago. Even so, they show definite benefits to small grains and corn from some types of shelterbelt protection, and it is thought that they provide a strong basis for deciding on shelterbelt width in establishing a shelterbelt system. Accordingly, a table and chart are presented that can be used to estimate total gains or losses in crop yield for shelterbelts of any width between 10 and 100 feet.

F–431275, 431276, 486501

FIGURE 21.—Comparative summertime density of three 1-row shelterbelts in Oklahoma: *A*, Cottonwood, 9 years old and 40 to 45 feet high. It is too open below for Oklahoma conditions, allowing considerable passage of wind through the lower half and causing some scouring action on the soil as the wind funnels through it. *B*, 9-year-old mulberry, spaced at 8 feet and now 20 feet high, makes a uniformly dense windscreen. *C*, Eastern redcedar 18 feet high and about 15 years old, makes a remarkably dense, uniform wind barrier winter and summer.

In figure 22, actual crop yields are expressed in terms of bushels or tons gained (+) or lost (−) for the field area entirely adjacent to one edge of a standard ½-mile shelterbelt. The black bars and plus (+) figures outside each white square represent any gains in fields lying north, east, south, and west of shelterbelts. Bars and minus (−) figures inside the white square represent any losses in yield for fields in the various locations. Losses due to sapping and shading by the trees in the area adjacent to the outer tree rows are included. The values have also been adjusted for normal unplanted field edge and for the normal field-edge effect for corn (fig. 11, p. 13).

No allowance has been made, however, for the area occupied by the shelterbelt. Crop loss on that area can be estimated from average yields for the unprotected parts of the fields sampled in the northern and central Great Plains on which the estimated benefits are based (table 1). The net effect of shelterbelts of varying width, averaging about 40 feet in height, can thus be estimated through the use of figure 22 and table 1.

For example, an average shelterbelt in Nebraska would just barely be paying for itself in additional crop yield of small grain in a field south of the belt if it were approximately 100 feet wide. The gain in yield is estimated from figure 22 at 110 bushels, and the unprotected yield on the area occupied by a 100-foot-wide shelterbelt is 103 bushels according to table 1.

For a field of small grain in the Dakotas protected by an east-west shelterbelt across and somewhere near its middle, the expected gain in yield on both sides of a ½-mile belt is 68+48, or 116 bushels. Even a belt of 110-foot width would at least break even in terms of current crop yield; effective, continuous narrow ones under 50 feet in width would leave a substantial gain in crop yield. This calculated protection value for well-developed shelterbelts must be discounted by about one-third to adjust for the period the trees require to reach their full height (see fig. 19 and its text).

In Kansas and Nebraska some of the shelterbelts referred to in figure 22 were osage-orange. These were often coppice growth and reduced crop yields on the field margin to a greater extent than most other trees in protective plantings. For this reason the average crop-yield benefits for belts devoid of coppiced osage-orange may be underestimated in these States.

Root Pruning To Reduce Shelterbelt and Crop Competition

Shelterbelts tend to depress growth of crops on nearby fields by sapping and shading to a distance

TABLE 1.—*Crop yields for ½-mile-long areas of varying width, based on average yields for unprotected parts of fields sampled in the northern and central Great Plains, 1935–40*

Area width (feet)	Kansas and Nebraska		North and South Dakota		
	Small grains	Ear corn	Small grains	Ear corn	Fodder corn
	Bushels	*Bushels*	*Bushels*	*Bushels*	*Tons*
10	10	15	11	21	1. 5
[1] 16. 5	17	26	18	34	2. 4
20	21	31	22	41	2. 9
30	31	46	33	62	4. 4
40	41	62	44	82	5. 8
50	52	77	54	103	7. 3
60	62	93	65	124	8. 7
70	72	108	76	144	10. 2
80	82	124	87	165	11. 6
90	93	139	98	185	13. 1
100	103	154	109	206	14. 5

[1] Equivalent to 1 acre. Crop yields associated with this width therefore are average values for the fields and crop years sampled.

of ½ to 1½ tree heights. For some plantings, especially single rows of osage-orange, the sapping zone may extend as far as 2 or 3 tree heights. The sapped zone is the largest, in terms of tree heights, for shelterbelts that have been cut back for fenceposts and then resprouted, since these in effect have the root spread of a full-grown plant but are much reduced in height.

Cutting of roots to reduce the sapping effect of a 56-foot-high shelterbelt permits growing normal crops within 23 feet of the trees, according to Panfilov (1932). Sutherland (1948) also suggested root pruning to reduce such sapping. It is used frequently in the citrus areas of California.

This treatment has been applied with success in the Great Plains. A trial near Carnegie, Okla., by the U.S. Bureau of Indian Affairs illustrates the favorable effects. A vertical cutting blade, mounted on a bulldozer blade on a crawler tractor, pruned tree roots to a depth of about 2 feet parallel to the shelterbelts and at a distance of about ½ tree height (fig. 23). Heavy sapping especially by Siberian elm and black locust had been observed. In some places depression of crop growth extended to 2 tree heights. After root pruning, even a sensitive crop like cotton (fig. 24) could be grown within ½ tree height. The cooperating farmer on whose land the work was done reported an additional yield of three bales of cotton on the zone immediately adjacent to the belt; this zone, before pruning of the tree roots, had been bare or had produced only stunted cotton plants.

The Oklahoma State Forest Service had similar good results near Mangum, Okla. A root cutter was made by welding a sharpened blade of steel to

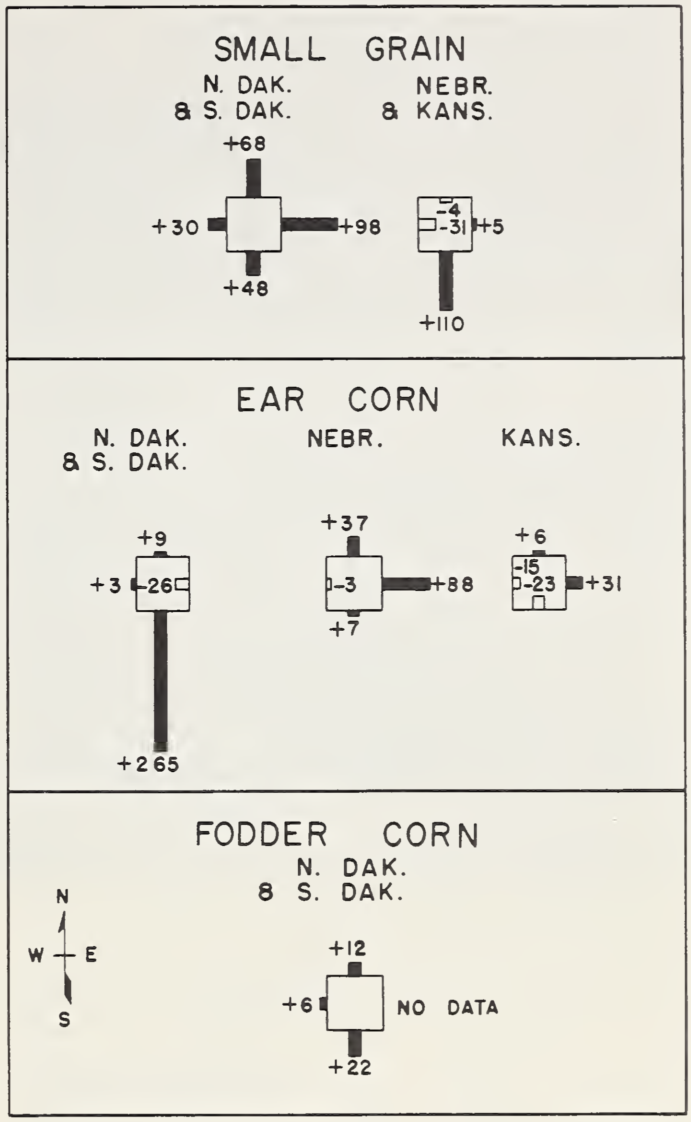


FIGURE 22.—Average gain or loss in crop yield from protection of a ½-mile-long shelterbelt as influenced by field location, type of crop, and orientation with respect to the shelterbelt. Central squares represent shelterbelt planting, and properly oriented bars represent gain or loss in crop yield. Small grain and ear-corn gains or losses are in bushels; those for fodder corn are in tons. (Basis: 94 fields of small grain and 184 of corn.)

a lister frame. It had a depth of cut of about 24 inches. The results were highly successful, and the treatments appear to be effective for at least a 3-year period.

A possible disadvantage of root pruning is danger of spread of certain root-rot diseases; these occur in some species of trees in the cotton-production areas of the southern Great Plains. Further research is necessary to determine the closest pruning distance that will result in a minimum of depression of tree growth, and how often pruning should be done.

Other Considerations

Although the data on crop-yield influence in this publication are for individual shelterbelts,

FIGURE 23.—Root pruning to reduce the sapping effect of a shelterbelt in western Oklahoma: *A*, Bulldozer with root-pruner blade in operation; *B*, closeup of the root-pruner blade mounted on front of the bulldozer blade. (Photo courtesy of U.S. Bureau of Indian Affairs.)

FIGURE 24.—The sapping effect observed on cottonfields in root-pruned and unpruned shelterbelts in western Oklahoma: *A*, Crop yield eliminated or drastically reduced in a zone equivalent to almost 2 tree heights; *B*, normal or better growth of cotton within ½ tree height of a root-pruned shelterbelt. (Photo courtesy U.S. Bureau of Indian Affairs.)

not patterns or systems of belts, there is evidence that a dense network of shelterbelts is of value. Multiple shelterbelts (fig. 25) seem to accomplish more in wind-erosion control than single, isolated plantings. For example, in Greer County, Okla., a marked difference in wind erosion is evident in an area with a concentration of plantings where rectangular fields of about 20 acres are completely surrounded by shelterbelts. The outer plantings in some instances have ridges of sand as much as 3 feet deep piled into or near the trees. The interior plantings show no appreciable drifting of sand. Soil movement is at a minimum where strip-cropping is used along with tree plantings. Apparently unobstructed winds sweeping across bare cotton or sorghum fields in the winter have carried the sand to the edge of the concentration of plantings and have dumped it there. Within the planted area there is no similar opportunity for buildup of eroded soil.

Shelterbelts trap drifting snow which otherwise may blow into ditches and roadways. To avoid blocking roads with snow in areas of appreciable snowfall, there should be at least 100 yards separating the shelterbelt from highways on the windward side. Generally, in the Great Plains, such a separation should be maintained on the west of north-south roads and on the north of east-west roads.

For highway safety, including the important factor of visibility for drivers of vehicles, any shelterbelt parallel and immediately adjacent to a road should end at least 100 yards from all road intersections.

Where the fields are level, farmers generally prefer to have shelterbelts oriented in cardinal directions, since field boundaries are based on rectilinear survey. Attempting to place shelterbelts more nearly at right angles to the most destructive winds will create many short rows and reduce the efficiency of mechanized farming. Most belts should be in an east-west direction. In rolling to moderately undulating terrain there may be some merit in placing shelterbelts on contours (Mironov 1935).

Spacing between east-west shelterbelts that will have an ultimate height of approximately 40 feet should be about 15 to 25 tree heights, or at intervals of about ⅛ to ⅕ mile; ⅛ mile is preferred on the more unstable sandy soils. For taller trees in the 50- to 70-foot range, ¼ mile between belts is adequate. Cross belts at twice the interval of the east-west belts make the system more effective. East-west belts should be of considerable length—preferably ¼ to ½ mile or more—since they afford relatively more protection per unit of length than very short, parallel belts where the wind sweeps around the end.

SCD–79482

FIGURE 25.—A community pattern of rectangular field shelterbelts near Dill City, Okla. The horseshoe-shaped and shorter belts at left center were designed to solve specific blowing problems and assist in special cropping plans.

Summary and Conclusions

There is a voluminous literature describing the favorable effects of shelterbelts on a variety of crops in various parts of the world. However, quantitative information on crop yields for conditions in the Great Plains is lacking. During 1935–41, crop-yield data were gathered from 286 fields adjacent to shelterbelts in the Great Plains. Corn, small grains, and cotton were sampled within the growth range of each from North Dakota to Texas and between the 98th and 100th meridians of longitude. Observations showed both favorable and unfavorable effects, depending on the type of crop, geographic location, and orientation of the tree plantings.

Fields of small grains in the Dakotas benefited substantially when protected, regardless of whether the belts ran east to west or north to south. In Nebraska and Kansas only those fields on the south and east of shelterbelts showed substantial benefit. A separate study in the Dakotas showed a greater response to protection for fields of lower inherent productivity. For the gross area of farmland protected by shelterbelts in the Dakotas (including the space occupied by the trees), the average annual gain in wheat yield is estimated at about 1 bushel per acre (67 kg. per hectare) over the entire lifespan of the belts. On sandy erodible soils it is expected to be more.

Ear corn in the Dakotas showed substantial gains only on fields south of shelterbelts. In Nebraska response was greatest to the east but only slightly less to the north and south. Response in Kansas was less than in Nebraska but showed the same relationship to shelterbelt orientation. In a separate study of Nebraska fields, the crop response was much greater in fields protected by dense shelterbelts than in those protected by shelterbelts of low density.

Cotton was sampled on eight fields in Oklahoma and Texas, seven of them north of the shelterbelt. Yields increased substantially to about 20 tree heights.

The zone in which crops show a large response is considerably narrower than the zone in which wind velocity or evaporation is reduced appreciably. Substantial wind reduction was observed over a distance of 25 or 30 tree heights to leeward and 5 tree heights to windward. Reduction

of water loss from evaporimeters extended a similar distance. Crop effects usually extended about half that distance.

Close to the windbreaks there is a marked depression of crop growth due to the sapping and shading effect of the trees. The sapping effect can be reduced by root pruning to a depth of 2 feet or more.

The effect of shelterbelts is particularly important in the northern half of the Great Plains where there is considerable snowfall. The additional snow trapped on the fields adds soil moisture for subsequent crop growth and is a prime factor in increasing crop yields near the shelterbelts. Properly located belts can reduce the amount of snow drifting onto roads and thus reduce highway maintenance costs.

In general, Great Plains shelterbelts oriented east and west are more effective than those oriented north and south. However, the geographic location of a field and type of crop to be grown on it are primary considerations.

Net gain from shelterbelt protection is directly related to the width of the strip in trees. Shelterbelt continuity and density improve with increasing width, but net benefits decrease if the belts are too wide. A narrow shelterbelt, preferably under 50 feet in width, and with good continuity and density, is the ideal for crop protection.

Literature Cited

Bagley, Walter T., and Gowen, Frederick A.
1960. Growth and fruiting of tomatoes and snap beans in the shelter area of a windbreak. Fifth World Forestry Cong. Proc., SP 171/VI, 6 pp.

Bates, Carlos G.
1911. Windbreaks: their influence and value. U.S. Forest Serv. Bul. 86, 100 pp., illus.

——— 1919. A new evaporimeter for use in forest studies. U.S. Monthly Weather Rev. 47: 283–294.

——— 1935. Climatic characteristics of the plains region. *In* Possibilities of shelterbelt planting in the plains region. U.S. Forest Serv. Spec. Bul., Sect. 11, pp. 83–110, illus.

——— 1944. The windbreak as a farm asset. U.S. Dept. Agr. Farmers' Bul. 1405, 22 pp., illus.

——— 1945. Wind movement in the plains. U.S. Forest Serv. Lake States Forest Expt. Sta. Tech. Note 245, 1 p. [Processed.]

——— 1948a. Farm crops benefit from field shelterbelts. Minn. Farm and Home Sci. 5(3): 6–7, illus.

——— 1948b. How shelterbelts benefit crops. Jour. Forestry 46: 767–768.

——— and Stoeckeler, J.H.
1942. Planting to control drifts on highways. Engin. News Rec. 129(23): 70–74, illus.

Bender, M.
1955. Einflusz des Windschutzes auf den Bodenertrag. Mitt. d. Dt. Landw.-Ges. 29: 767. [Abstracted by G. Raschke in Die Holzzucht 10(1): 1–8. 1956.]

Beskök, Turgut E.
1957. [Shelterbelts and experiments on the establishment of shelterbelts in Balâ.] Ormancilik Araştirma Enstitüsü Neşriyati, Teknik Bül. Ser. 7, 138 pp., illus. [In Turkish. English summary, pp. 130–133.]

Bodroff, B. A. [Bodrov, V. A.]
1935. [Influence of shelterbelts on the microclimate of the adjoining territory.] Vsesoîuzn. Naouch.-Izsled. Lesokult. i. Agrolesomelior. Inst., pp. 1–83. [U.S. Forest Serv. Transl. 164.]

Bodrov, V.
1936. The influence of shelterbelts over the microclimate of adjacent territories. Jour. Forestry 34: 696–697.

Bülow, A. von
1951. Windschutzfibel: kurze Anleitung zur Knickanpflanzung und Odlandaufforstung (A primer of protection against wind: a short guide to hedge planting and afforestation of waste land). 39 pp. Rendsburg, Germany. [Forestry Abs. 14: 169–170. 1953.]

Caborn, J. M.
1956. Width and cross-sectional profile in shelterbelts. Internatl. Union Forest Res. Organ. Cong. 12, 7 pp.

——— 1957. Shelterbelts and micro-climate. [Gt. Brit.] Forestry Comn. Bul. 29, 135 pp., illus.

Catrina, I., and Marcu, G.
1955. Contribuţii la cumoasterea influenţei perdelelor forestiere asupra umezelii solului în cîmpul vecin (The influence of shelterbelts on the soil moisture of adjacent fields). Bul. Şti. Acad. Repub. Rom. (Sect. Biol.) 7: 1011–1026. [Forestry Abs. 17: 538. 1956.]

Chepil, W. S.
1953a. Factors that influence clod structure and erodibility of soil by wind: 1. Soil texture. Soil Sci. 75: 473–483, illus.

——— 1953b. Factors that influence clod structure and erodibility of soil by wind: 2. Water-stable structure. Soil Sci. 76: 389–399, illus.

——— 1954. Factors that influence clod structure and erodibility of soil by wind: 3. Calcium carbonate and decomposed organic matter. Soil Sci. 77: 473–480.

Chernikov, F. S.
1951. [The water regime of light chestnut-brown soil in the open and under shelterbelts.] Lesnoye Khoz. 11: 16–18. [U.S. Forest Serv. Transl. 371.]

Dambach, C. A.
1948. A study of the ecology and economic value of crop field borders. Ohio State Univ. Grad. School Studies (Biol. Sci. Ser.) 2: 205. [Forestry Abs. 11: 470–471. 1950.]

Dautov, R. K.
1953. [Effect of forest shelterbelts on the depth of snow cover and soil freezing.] Dok. Akad. Nauk SSSR 89: 555–556. [Forestry Abs. 15: 49. 1954.]

Den Uyl, Daniel.
1936. The zone of effective windbreak influence. Jour. Forestry 34: 689–695, illus.

D'YACHENKO, A. E., AND ZEMLYANITSKI, L. T.
1946. [MEASURES AGAINST DUST STORMS IN BASHKIR.] Nauch. Otchet VNIALMI za 1941–1942: 4–33. [Forestry Abs. 9: 178–179. 1948.]

EDWARDS, C. A.
1939. FIELD CROP SHELTERBELTS IN WESTERN CANADA. Forestry Chron. 15: 99–102.

FERBER, A. E., FORD, A. L., AND MCCRORY, S. A.
1955. GOOD WINDBREAKS HELP INCREASE SOUTH DAKOTA CROP YIELDS. S. Dak. State Col. Agr. Expt. Sta. Cir., 118, 16 pp., illus.

GEORGE, ERNEST J.
1943. EFFECTS OF CULTIVATION AND NUMBER OF ROWS ON SURVIVAL AND GROWTH OF TREES IN FARM WINDBREAKS ON THE NORTHERN GREAT PLAINS. Jour. Forestry 41: 820–828, illus.

———
1953. TREE AND SHRUB SPECIES FOR THE NORTHERN GREAT PLAINS. U.S. Dept. Agr. Cir. 912, 46 pp., illus.

GORDIENKO, M.
1953. DER EINFLUSS DES WALDES. BZW. DER WALDSCHUTZSTREIFEN AUF DIE WASSERVERHÄLTNISSE UND DEN GRUNDWASSERSTAND IM BODEN (THE INFLUENCE OF FORESTS AND SHELTERBELTS ON SOIL-WATER REGIME AND THE WATER-TABLE). Deut. Landw. 4(1): 43–46. [In German.]

GORSHENIN, N. M.
1941. [AGRO-FOREST AMELIORATION.] 392 pp., illus. Moscow. [In Russian.]

——— PANFILOV, Y. D., GODOUNOFF, N. T., AND OTHERS.
1934. [IMPROVEMENT OF FARMLAND IN THE IRRIGATED REGION OF THE ZAVOLJIE.] Moscow, Goslestechnizdat. 143 pp. (USSR All-Union Inst. of Forest Culture and Forest Melioration, Expts. 4.) [U.S. Forest Serv. Transl. 64.]

GOVIADIN, Z.
1933. [THE FOREST IN THE SERVICE OF AGRICULTURE.] *In* LESS-NA SLUJBU SOCIALISTICHESKOMU STROITELSTUU. Moscow. [U.S. Forest Serv. Transl. 35.]

HAYS, F. A., AND STOECKELER, J. H.
1935. SOIL AND FOREST RELATIONSHIPS OF THE SHELTERBELT ZONE. *In* POSSIBILITIES OF SHELTERBELT PLANTING IN THE PLAINS REGION. U.S. Forest Serv. Spec. Bul., Sect. 12, pp. 111–153, illus.

IGNATIEV, S. N.
1940. SHELTERBELTS AND YIELD OF PERENNIAL FORAGE CROPS. All-Union Acad. Agr. Sci. Trans., Plant Prod. Sect., Lenina 3: 9–13.

JENSEN, M.
1954. SHELTER EFFECT: INVESTIGATIONS INTO THE AERODYNAMICS OF SHELTER AND ITS EFFECTS ON CLIMATE AND CROPS. 264 pp., illus. Copenhagen. [Forestry Abs. 16: 216. 1955.]

JONES, M. D., AND BROOKS, J. S.
1952. EFFECT OF TREE BARRIERS ON OUTCROSSING IN CORN. Okla. Agr. Expt. Sta. Tech. Bul. T–45, 11 pp., illus. [Forestry Abs. 14: 170. 1953.]

KARUZIN, B. V., AND SHESTOPEROV, G. P.
1936. [A STUDY OF THE NARROW SHELTERBELTS IN THE TIMASHEV DISTRICT, KUIBYSHEV REGION.] Rpt. of the All-Union Res. Inst. for the Impr. of Farmland by Forestation 6: 117–169. [U.S. Dept. Agr. Libr. Transl. 7311.]

KIBASOV, P.
1955. [EFFECTIVENESS OF VARIOUS METHODS OF SNOW RETENTION IN SIBERIA.] Zeml. 3: 60–61. [U.S. Forest Serv. Transl. 375.]

KUCHERYAVYKH, E. G.
1940. [THE EFFECT OF SHELTERBELTS OF DIFFERENT STRUCTURE ON CROP YIELDS.] Sovet. Agron. 10: 18–22. [In Russian.]

KUMMER, E.
1955. FLURBEREINIGUNG UND WINDSCHUTZ. Die Holzzucht 9: 17–21, illus. [In German.]

LINDE, R. J. VAN DER
1948. HOUTOPSTANDEN EN BODEMVERSTUIVING (TREE PLANTING AND WIND EROSION). Maandbl. Landbouwvoorlichtingsdienst, 's-Gravenhage 5: 530–536. [Forestry Abs. 12: 465. 1951.]

——— AND WOUDENBERG, J. P. M.
1951. ON THE MICROCLIMATIC PROPERTIES OF SHELTERED AREAS: THE OAK-COPPICE SHELTERED AREA. Meded. Inst. Toegep. Biol. Onderz. Nat. 10, 151 pp., illus. [Forestry Abs. 13: 173. 1951.]

LUPE, I.
1954. [THE INFLUENCE OF FORESTS AND SHELTERBELTS ON CLIMATE AND AGRICULTURAL CROPS.] Rev. Pădurilor 69: 170–175, illus. [Forestry Abs. 16: 217. 1955.]

MARAN, B., AND LHOTA, O.
1952. [MICROCLIMATIC STUDIES ON EVAPORATION.] Lesn. Práce. 31: 198–206. [Forestry Abs. 14: 291. 1953.]

MASINSKAJA, L. P.
1950. [ESTABLISHING SHELTERBELTS IN VINEYARDS.] Vinodel. i. Vinograd. SSSR Moskva 10: 22–24. [Forestry Abs. 15: 181–182. 1954.]

MATIAKIN, G. I.
1934. [ROSTASHI SHELTERBELTS.] *In* Opyty i Issledovania (Experiments and Investigations) 5: 27–68. [U.S. Forest Serv. Transl. 153.]

———
1937. [SHELTERBELTS PROTECTING FARMLAND IN THE SEMI-DESERT AND THEIR INFLUENCE ON THE MICROCLIMATE OF THE INTERMEDIATE SPACES.] Polezashtchitnye polossy (shelterbelts), Rpt. of the All-Union Sci. Res. Insti. for the Impr. of Farmland by Forestation 8: 65–119. [U.S. Forest Serv. Transl.]

MATSUI, Z., AND YOKOYAMA, C.
1955. [ON THE EFFICIENCY OF THE WIND-BREAK HEDGE IN PROTECTING THE RICE CROP IN HOROMUI DISTRICT.] Hokkaido Forest Expt. Sta. Spec. Rpt. 3: 168–177. [Forestry Abs. 16: 514–515. 1955.]

METCALF, WOODBRIDGE.
1936. THE INFLUENCE OF WINDBREAKS IN PROTECTING CITRUS ORCHARDS. Jour. Forestry 34: 571–580, illus.

MIRONOV, A.
1935. [FORESTATION AND COMBATING DROUGHT.] Khoz. (Planned Management), No. 5: 108–122. [U.S. Dept. Agr. Libr. Transl. 7313.]

NÄGELI, W.
1943. UNTERSUCHUNGEN ÜBER DIE WINDVERHÄLTNISSE IM BEREICH VON WINDSCHUTZSTREIFEN (INVESTIGATIONS ON WIND CONDITIONS IN THE VICINITY OF WINDBREAKS). Mitt. Schweiz. Anst. Forstl. Versuchsw. 23: 223–276. [Forestry Abs. 6: 92. 1944.]

———
1946. WEITERE UNTERSUCHUNGEN ÜBER DIE WINDVERHÄLTNISSE IM BEREICH VON WINDSCHUTZSTREIFEN (FURTHER STUDIES ON WIND CONDITIONS IN THE VICINITY OF WINDBREAKS). Mitt. Schweiz. Anst. Forstl. Versuchsw. 24: 659–737. [Forestry Abs. 9: 57. 1947.]

OLBRICH, ANTON.
1949. WINDSCHUTZPFLANZUNGEN (SHELTERBELTS). 83 pp., illus. Hannover.

PANFILOV, J.
1932. [THE INFLUENCE OF SHELTERBELTS.] Na Lesokulturnom Fronte 7–8: 2–18. [U.S. Forest Serv. Transl. 228.]

———
1937. [SHELTERBELTS ON THE WATERSHED PLATEAU OF THE PRAIRIE ZONE OF THE VOLGA REGION.] Polezashtchitnye Polossy (shelterbelts), Rpt. of the All-Union Sci. Res. Inst. for Impr. of Farmland by Forestation 8: 3–64. [U.S. Dept. Agr. Libr. Transl. 7315.]

PAVARI, A., AND GASPARINI, M.
1943. L'AZIONE DI DIFESA DEI FRANGIVENTI SULLA CULTURA GRANARIA (THE PROTECTIVE EFFECT OF WINDBREAKS ON CEREAL CULTIVATION). 34 pp. Florence. [In Italian.]

POTTER, L. D., LONGWELL, JOHN, AND MODE, CHARLES.
1952. SHELTERBELT SNOW DRIFTS. N. Dak. Agr. Expt. Sta. Bimo. Bul. 14(5) : 176–179.

QUAYLE, W. L.
1941. SHELTERBELT INCREASES HAY YIELDS. *In* PRACTICAL RESULTS FROM THE STATE EXPERIMENT FARMS. Wyo. Agr. Expt. Sta. Bul. 243, 9 pp., illus.

READ, RALPH A.
1958. THE GREAT PLAINS SHELTERBELT IN 1954. Great Plains Agr. Council Pub. 16, Univ. Nebr. Expt. Sta. Bul. 441, 125 pp., illus.

RHEE, J. A. VAN
1957. THE CROPPING OF FRUIT TREES IN RELATION TO WINDBREAK PROTECTION. Inst. voor Topegast. Med. 33 : 11–17.

SATOO, T.
1952. [NOTES ON THE WATER RELATIONS OF TREES AND WINDBREAKS.] Tokyo Univ. For. Misc. Inform. 9 : 26–30. [Forestry Abs. 14 : 291. 1953.]

SHAPOSHNIKOV, A. P.
1946. [GROWTH AND INFLUENCE ON CROP YIELDS OF TREE PLANTATIONS FOR EROSION CONTROL IN THE CENTRAL FOREST STEPPE.] Nauch. Otchet VNIALMI za 1941–1942: 82–90. [Forestry Abs. 9: 174–175. 1947.]

SOEGAARD, BENT.
1954. OUTLINE OF SHELTERBELTS AND SHELTERBELT TESTS IN DENMARK. Cong. Internatl. Union Forest Res. Organ. Proc. 11 : 246–269, illus.

SOKOLOVA, N. S.
1937. [INFLUENCE OF SHELTERBELTS ON THE YIELD OF AGRICULTURAL PLANTS (GRAINS, PRODUCTS OF TRUCK FARMING, AND OIL-BEARING PLANTS).] Polezashtchitnye Polossy (shelterbelts), Rpt. of the All-Union Sci. Res. Inst. for the Impr. of Farmland by Forestation 8 : 120–158. [U.S. Dept. Agr. Libr. Transl. 7317.]

SØRENSEN, HAKON.
1952. KAN LAEPLANTNING GIVE OS STØRRE AFGRØDER (CAN SHELTERBELTS GIVE US LARGER YIELDS?). Jydsk. Landbr. 34: 586–587. [Transl. by Hans Nienstaedt; on file at Lake States Forest Expt. Sta.]

STAPLE, W. J., AND LEHANE, J. J.
1955. THE INFLUENCE OF FIELD SHELTERBELTS ON WIND VELOCITY, EVAPORATION, SOIL MOISTURE, AND CROP YIELD. Canad. Jour. Agr. Sci. 35 : 440–453, illus.

STEUBING, L.
1952. DER TAU UND SEINE BEEINFLUSSUNG DURCH WINDSCHUTZANLAGEN (DEW AND THE INFLUENCE OF WINDBREAKS ON IT). Biol. Zbl. 71 : 282–313. [Forestry Abs. 14 : 53. 1953.]
1954. EXPERIMENTELLE UNTERSUCHUNGEN ÜBER DIE VERÄNDERUNG DER STANDORTSFAKTOREN DURCH WINDSCHUTZANLAGEN (EXPERIMENTAL STUDIES ON THE MODIFICATION OF SITE FACTORS BY SHELTERBELTS). Oikos (1952–1953) 4: 118–147. [Forestry Abs. 16: 65–66. 1955.]

STOECKLER, J. H.
1945. NARROW SHELTERBELTS FOR THE SOUTHERN GREAT PLAINS. Soil Conserv. 11 : 16–20, illus.

——— AND BATES, C. G.
1939. SHELTERBELTS : THE ADVANTAGES OF POROUS SOILS FOR TREES. Jour. Forestry 37 : 205–221, illus.

——— AND DORTIGNAC, E. J.
1941. SNOWDRIFTS AS A FACTOR IN GROWTH AND LONGEVITY OF SHELTERBELTS IN THE GREAT PLAINS. Ecol. 22 : 117–124, illus.

——— AND WILLIAMS, ROSS A.
1949. WINDBREAKS AND SHELTERBELTS. U.S. Dept. Agr. Yearbook 1949 : 191–199, illus.

SUSS, N. I.
1932. [FORESTATION OF FARMLAND AND ITS IMPORTANCE IN COMBATING CROP FAILURES.] Na Lesokulturnom Fronte 1 : 12–21. [U.S. Forest Serv. Transl. 120.]

———
1935. [ACHIEVEMENTS IN THE IMPROVEMENT OF AGRICULTURAL LANDS BY FORESTATION.] From Selskoe Khoz. SSSR Ezhegodnik 1935 : 172–183. [U.S. Forest Serv. Transl. 286.]

———
1944. [MEASURES FOR RURAL AMELIORATION WITH THE AID OF FORESTRY, AND SCIENCE DURING THE WAR AND POST-WAR PERIODS.] Byull. Inst. Khoz. yu-v. SSSR 3 : 3–13. [Forestry Abs. 7 : 476. 1946.]

SUTHERLAND, M.
1948. MULTI-PURPOSE TREES FOR PLANTING ON FARMS. New Zeal. Jour. Agr. 77 : 19–25. [Forestry Abs. 10 : 340. 1949.]

THRAN, P.
1952. ERTRAGSSTEIGERUNGEN DURCH DEN WINDSCHUTZ DER WALLHECKEN (KNICKS) IN SCHLESWIG-HOLSTEIN (INCREASED YIELDS BY SHELTER FROM WIND AFFORDED BY HEDGES ON EARTH WALLS IN SCHLESWIG-HOLSTEIN). Ber. des deut. Wetterdienstes in der US-Zone, Bad Kissingen 32 : 57–59. [Forestry Abs. 15 : 49. 1954.]

TRENK, F. B.
1948. INFLUENCE OF PLANTED TREE BELT IN PLAINFIELD SAND ON EROSION CONTROL AND MOISTURE CONSERVATION. Iowa State Col. Jour. Sci. 22 : 449–461, illus. [Forestry Abs. 10 : 341. 1949.]

WILLIAMS, R.
1949. TREES THAT BEAT THE BLIZZARD. Amer. Forests 55(8) : 26–27, 42–43.

WOODRUFF, N. P., READ, R. A., AND CHEPIL, W. S.
1959. INFLUENCE OF A FIELD WINDBREAK ON SUMMER WIND MOVEMENT AND AIR TEMPERATURE. Kans. Agr. Expt. Sta. Tech. Bul. 100, 24 pp., illus.

ZYKOV, I. V.
1951. [PECULIARITIES OF SNOW-MELTING AND THE IMPORTANCE OF SHELTERBELTS IN THE FOREST-STEPPE OF SIBERIA.] Priroda, Moskva 40 : 54–57. [Forestry Abs. 13 : 173. 1951.]

U.S. GOVERNMENT PRINTING OFFICE : 1962 O—641754